THE ELECTRICAL CONDUCTIVITY OF THE ATMOSPHERE AND ITS CAUSES

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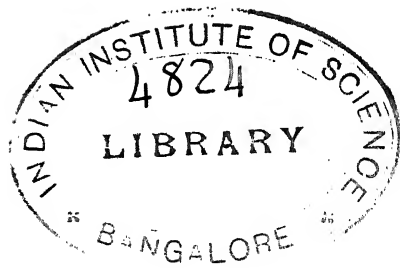BY

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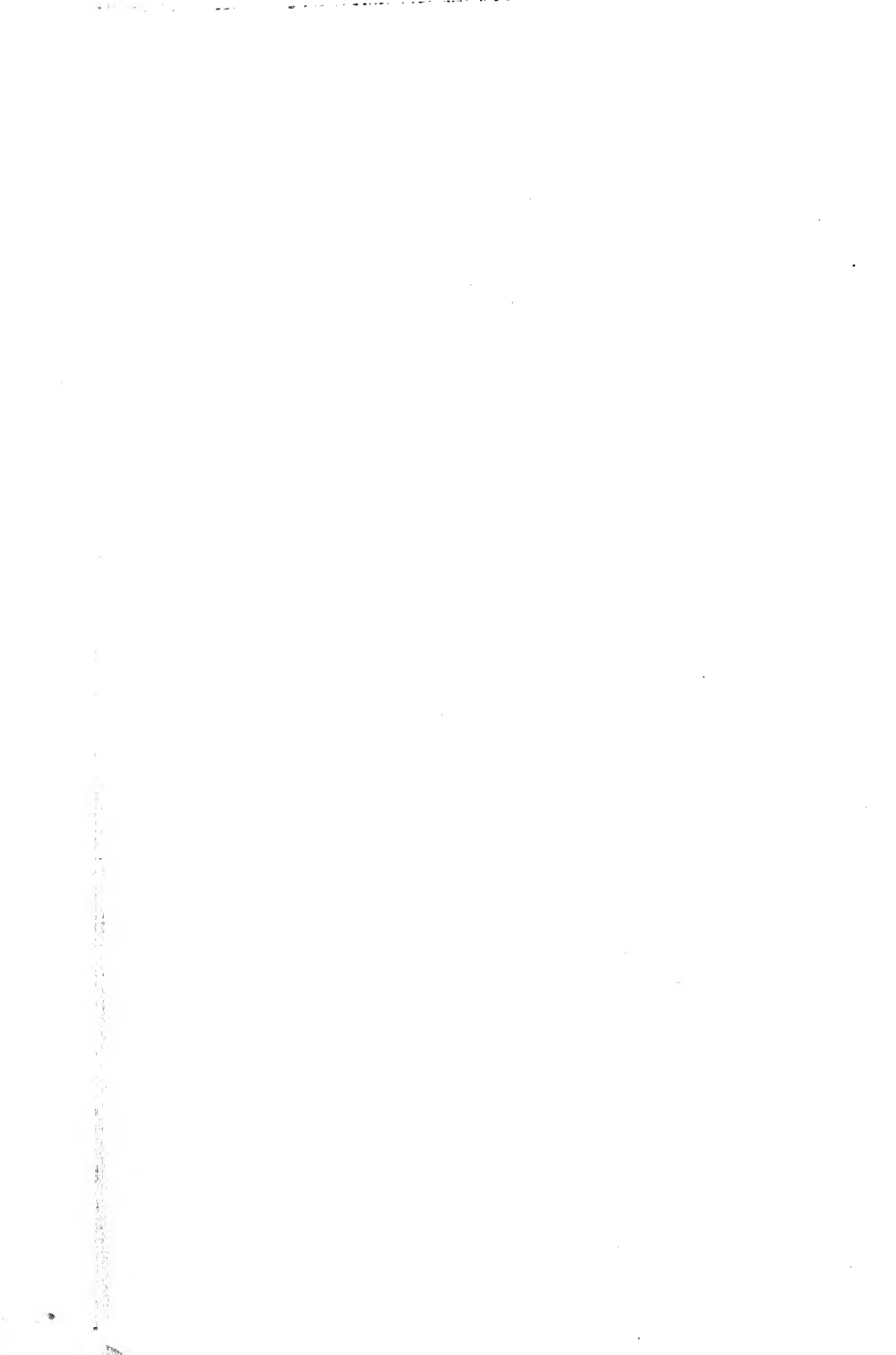
AUTHOR'S PREFACE TO THE ENGLISH EDITION

WHEN it was decided in January, 1927, to prepare an English edition of the present work, the German edition had already been published some six months. On account of the extraordinarily rapid progress which had been made in certain branches of atmospheric electricity, it was necessary to rewrite two chapters completely : that on ultra-gamma radiation (*höhenstrahlung*) (§ 23), and that on the properties and ionisation of the highest layers of the atmosphere (§ 28). In doing so the most important work of 1926 was taken into account, as far as it was available in January, 1927. The remainder of the work is essentially unaltered, except for a few minor additions. I hope that the book may prove of interest to English readers, more especially as it is the only general treatise on Atmospheric Ionisation which has so far appeared in the English language.

Finally, I have to thank the translator of the book, Mr. L. W. Codd, for the painstaking work which has rendered the revision of the English translation by myself an easy task.

V. F. HESS.

HELIGOLAND,
June, 1927.
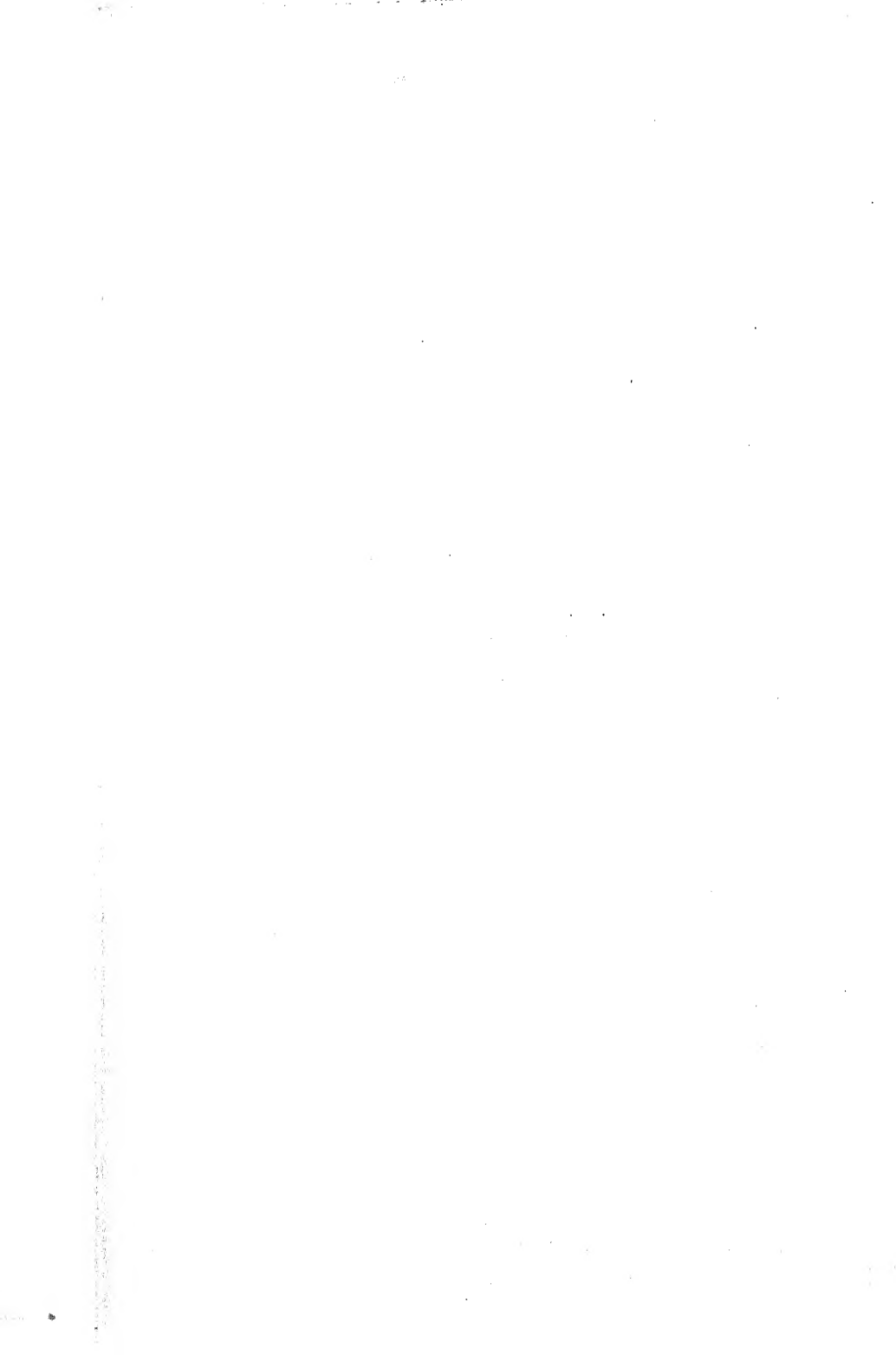
AUTHOR'S PREFACE

It is now almost twenty years since the appearance of the most recent comprehensive works (in German) on Atmospheric Electricity—the monographs of A. Gockel (1908), and of H. Mache and E. v. Schweidler (1909). The progress which has been made during the interval is quite comparable with that of the period 1899 to 1909, when the application of the laws of gas ions and the discovery of radioactive substances in the ground, the rocks, the sea and the atmosphere opened a new field for the investigation of atmospheric electricity.

Our knowledge of the conduction of electricity in the atmosphere has been extended in many essential particulars, and the electrical relationships in the atmosphere over the ocean have been fully explained by the extended experimental voyages of the Carnegie Institution of Washington in all seas. A new source of ionisation has been discovered during balloon ascents in Europe : a radiation of high penetrating power which enters the earth's atmosphere from above, the so-called "*höhenstrahlung*" (ultra-gamma radiation). The action of this and other ion-forming factors at the earth's surface and within the first ten kilometres of the atmosphere (troposphere) is now fairly well known both qualitatively and quantitatively.

Fresh knowledge has also been obtained, from various sources, of the higher layers of the atmosphere (stratosphere), where the phenomena of the aurora take place, and where the high conductivity is of such importance for the transmission of the waves employed in radio-telegraphy and telephony.

In another direction, the investigation of the recombina-

tion of ions, and other processes bringing about the destruction of ions, has made great advances. It has thus become possible to obtain—at least for the troposphere—a picture, concordant in itself and in good agreement with observation, of the mean activity of the processes producing and destroying ions. There is still, however, a long way to go before all the details of the regular variations of conductivity and ionisation and similar phenomena can be explained.

For the very reason that this branch of atmospheric electricity seems to have reached a definite state—at least in its main points—it seemed desirable to give in this work a summary of our knowledge of the ionisation of the atmosphere and its causes.

The book is addressed to a wide circle of readers—to those interested in geophysics, in meteorology, and particularly in aerology ; to those concerned with radio-telegraphy and telephony, with geology and astronomy, with electrotechnics ; to ocean and aerial navigators, and also to the general reader, I hope that much in the book may appeal. For the benefit of the general reader, the introductory sections on the laws of gas ions, conductivity in gases, and the fundamentals of radioactivity are given at suitable places. As far as possible the methods of observation and the results are kept apart in the various sections.

The bibliography is fairly complete, both as regards the more important new investigations and the older fundamental work, and the reader will therefore be able to go more deeply into any special question if he should wish. It is, however, obviously impossible in a book of this kind to quote all the work and experimental results of lesser importance. The bibliography extends to the end of 1925, but in certain sections, where recent rapid advances made it necessary (§§ 23, 28), even later work—up to March, 1926—has been included.

A complete bibliography will be given in a more extensive work on the whole field of atmospheric electricity by Professor Hans Benndorf (Graz) and myself, which is in contemplation.

It is with great pleasure that I express my thanks to the colleagues who have helped by the sending of reprints, private communications and advice. Among these I should like to mention in particular Dr. Louis A. Bauer, Director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, D.C., U.S.A. ; Professor Dr. A. Gockel, Freiburg, Switzerland (died in 1927) ; Professor A. F. Kovarik, New Haven ; Professor Dr. E. Schweidler, Innsbruck ; and Professor Dr. A. Wigand, Stuttgart-Hohenheim.

<div align="right">VICTOR F. HESS.</div>

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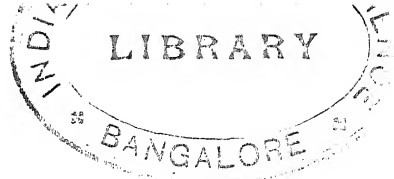
THE

ELECTRICAL CONDUCTIVITY OF THE ATMOSPHERE

CHAPTER I

INTRODUCTION

§ 1. Electrical Conductivity, the Electric Field, and the Electric Currents in the Atmosphere—Fundamental Facts.

THE first attempts at an investigation of electrical conduction in the atmosphere date back to the time of Coulomb (1785), who showed that a metallic conductor, placed in air, gradually loses its charge in a manner to be ascribed not only to faulty insulation, but also, to some extent, to the conduction of electricity away from the body into the air.

As late as 1880 but few workers had taken up the closer investigation of this phenomenon ("dissipation of charge"). The false idea that damp air conducts electricity better than dry air was thus able to persist for a whole century, and the few exact experiments which contradicted it passed unheeded. Among these may be mentioned, in particular, the researches of C. Matteucci [1] and E. Warburg. [2]

In 1887, F. Linss [3] showed that the loss of charge is greatest during fine weather, i.e., when the air is dry ;

[1] *Ann. Chim. Phys.* (3), **27**, 133 (1849) ; **28**, 385 (1850).
[2] *Pogg. Ann.*, **145**, 578 (1872).
[3] *Meteorol. Zeitschr.*, **4**, 345 (1887) ; *Elektrot. Zeitschr.*, **11**, 506 (1890).

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he found, also, that the loss in a given time varied in a regular manner with the season of the year.

In the light of what was then known of the conduction of electricity through gases, no satisfactory explanation of the dissipation of electrical charges was forthcoming.

The first notable advance was brought about by the discovery and investigation of Röntgen and Becquerel rays. It was learnt that the conductivity of all gases may be increased artificially to an enormous extent by the action of these rays, and from this fact emerged the theory of ionic conduction in gases. In the light of this theory, gases, just as electrolytes, contain positively and negatively charged particles (*e.g.*, atoms, molecules or molecular groups), which move under the influence of an electric field in a direction determined by the sign of their charge : these particles are called gas ions. The application of the theory of gas ions to the facts of electrical conduction in atmospheric air is due to the two German investigators J. Elster and H. Geitel who succeeded in offering a satisfactory explanation of the processes responsible for the dissipation of an electric charge.

Coulomb had assumed that the particles suspended in the surrounding air, dust and water vapour, for example, first become charged by contact with the electrified body, and then carry away its charge ; it was now proved that charged particles—the ions—may exist in gases quite independently of the presence of a charged body. The " dissipation " of electricity thus consists, not in the dispersion of the charge in the air, but in its neutralisation by ions of opposite sign drawn to the surface of the body by electrostatic attraction.

Any treatment of the investigation of electrical conduction in the atmosphere must therefore begin, as a matter of course, with an exposition of the fundamental laws of gas ions.

Before entering upon this, a few words may be said

regarding the electric field existing in the atmosphere. It has been known ever since the researches of Le Monnier (1752) that there exists always and everywhere, even on fine days, a permanent electrical potential difference between the earth and the air. This potential difference, measured with an electroscope between the earth's surface and a point 1 metre above it, amounts, on an average, to 100 to 300 volts, according to the season. Higher points at, say, 2, 3 or 4 metres above the earth's surface, have potential differences of approximately two, three and four times this amount. In the atmosphere therefore there is a potential gradient, varying with time and place, of some 100 to 300 volts per metre, measured in a vertical direction ; in other words, there exists between earth and atmosphere an electric field, which may be shortly referred to as the earth's field. The earth's field is, of course, only active in its full strength in open country, for under trees or other electrically conducting obstacles the air is protected from its influence. At increasing heights the potential gradient diminishes rapidly.

The existence of this electric field, together with the fact that the atmosphere is a conductor, results in a permanent vertical flow of electricity. Since the earth appears normally to be negatively charged in relation to the atmosphere, positive electricity usually flows towards the surface of the earth. The mean intensity of this vertical current amounts to 2.10^{-16} amps. per square centimetre. Integrated over the whole of the earth's surface, this would correspond to a constant total current of more than 1,000 amps.

The vertical currents due to conductivity are not the only ones occurring in the atmosphere, " convection currents " being also of considerable importance. By the latter are meant the quantities of electricity which are brought to earth through the agency of rain drops, snowflakes and the like.

All these phenomena, together with lightning, earth currents, etc., form the subject matter for investigations in the domain of atmospheric electricity. The present work is confined to one branch only. For the benefit of those who require information covering the whole field, a list, both of the shorter and the more complete treatises on this subject is given in the appendix.

CHAPTER II

THE CONDUCTIVITY OF THE ATMOSPHERE

§ 2. Fundamental Properties of Gas Ions.

IT is an experimentally well proved fact that all gases contain positively and negatively charged carriers of electricity, which may be shortly referred to as " carriers " or " ions." The charge on an ion is equal to the elementary quantum of electricity or elementary charge, i.e., $4 \cdot 77 \cdot 10^{-10}$ electrostatic units. Ions with multiple charges are of comparatively rare occurrence. The masses of the gas ions vary within very wide limits.

Let us now consider any gas—air, for example—contained in the space between two metal plates, one of which is earthed, while the other is connected with a source of high potential. Ordinary air always contains ions, derived for the most part from the radiation of the radioactive substances which are always present in minute quantities in the atmosphere and in the crust of the earth.

Upon applying the potential the ions will be set in motion, those with positive charges moving along the lines of force, those with negative charges in the opposite direction. The velocity of all the ions will increase until the frictional resistance becomes equal to the accelerating force. This condition will be reached, as may be shown by a simple calculation, in less than 10^{-5} seconds, even in the case of the heaviest ions, after which each kind of ion will move towards the electrodes with a characteristic velocity depending only upon its dimensions and upon the field strength. On reaching the electrode each ion will give up its charge.

The velocity of the gas ions is proportional to the field strength, and the velocity of an ion in a field of unit strength (expressed usually in volts per centimetre) is known as the mobility of the ion. Ionic mobilities will be represented in the following pages by k_+ and k_- for positive and negative ions respectively.

In general, two main classes of ions may be distinguished: the small (mobile) ions and the large (less mobile) ions. On account of the difference in their sizes, the behaviour of the two classes in an electric field is by no means the same. In addition to these two, there is a third class, consisting of the electrons, which, however, can only carry a negative charge. These electrons, well known in a state of rapid motion in the form of kathode rays, and as the β-rays of radioactive elements, are only in a few instances perceptible in gases at atmospheric pressure, as in the purest nitrogen, in helium, argon, and others of the inert gases. Thus J. Franck succeeded in showing that the mobility of the negative ions in these gases is about one hundred times that of the positive ions; while in air, oxygen, carbon dioxide, etc., the negative ion moves only about one and a half times as quickly as the positive ion. The abnormally high mobility of the negative ion in nitrogen, which points to abnormally small dimensions, is immediately reduced to the usual small value by the admixture of the slightest trace of another gas, e.g., oxygen.

Electrical "carriers" in the form of electrons can, therefore, apparently exist in gases permanently—i.e., without attaching themselves to gas molecules—only in special instances, e.g., in purified nitrogen. In order to explain this behaviour, Lenard assumes that each individual electron alternately attaches itself to, and breaks away from, the gas molecules, the process occurring in a similar manner in all gases. In nitrogen and the rare gases the ions formed by the addition of an electron to a

gas molecule must be less stable than those formed in gases such as oxygen or air. Franck, on the other hand, advances the view that the readiness with which various gaseous elements attract electrons ("electron-affinity") is essentially different in different cases. E. M. Wellisch has proposed a third point of view, adopting the idea of Lenard as to the alternate binding and setting free of electrons, together with the suggestion that various gases contain different percentages of free electrons, the percentage in any given case depending upon the pressure of the gas. At present it is impossible to reach a final decision between the three theories.

Since no abnormally large mobility of the negative ions can be detected in air, it follows that in air at atmospheric pressure free electrons are not present in appreciable quantities.

We will now turn to the consideration of the two principal classes of ions which cause the conduction of electricity in the atmosphere.

1. The "Light" or "Small" Ions (often called "molecular ions").—The mobility of the majority of the normal "small" ions of both signs in dust-free air is about 1 to 2 cm. per second for a field strength of 1 volt per centimetre ; it is thus considerably smaller than the value theoretically calculated on the assumption that the dimensions of these ions are no larger than those of a single molecule or atom.

It is therefore assumed that these normal or "small" ions consist of groups of some 10 molecules, more or less, grouped around a central charged molecule and forming a fairly stable complex or cluster.

Single charged atoms or molecules are, as experiments show, not stable in gases at normal pressure, since, by attracting other atoms, they readily form the "small" complex ions mentioned above.

It will be shown later that these "small" ions, whose

velocity is of the order of 1 cm./sec. : volt/cm. in air at atmospheric pressure, are responsible for the greater part of the conductivity of the free atmosphere.

2. **The "Heavy" or "Large" Ions** (also called Langevin ions).—When the positively or negatively charged "small" ions or electrons in a gas combine with the so-called "condensation nuclei" or with drops of water vapour, ions of very much larger mass are produced, which are called "heavy" ions or "Langevin ions," after their discoverer, P. Langevin. We may call them "large" ions, since the mobility of such particles in a resisting medium such as air depends more on their size (cross-sectional dimensions) than upon their mass. The large ions, on account of their size, move very much more slowly in an electric field than do the small ions. They are present in large numbers even in pure country air, and to a much greater extent, of course, in town air polluted with products of combustion. Their mobility may vary within wide limits according to their size : the largest have a mobility of 0·0005 cm./sec. : volt/cm., and the smallest a mobility of about 0·01. Between these large ions and the small ions of mobility 1 cm./sec. : volt/cm. there are also the so-called intermediate ions discovered by Pollock in Sydney ; these can, however, apparently only exist under certain conditions of humidity. Their mobility is at least ten times smaller than that of the light ions, and in their nature they resemble rather the large ions.

The differences in the mobilities of the small and large ions are best seen by calculating the time required for the passage of an ion from one plate of an air condenser to the other under definite conditions. If, for example, the plates are 10 cm. apart and the potential difference is 200 volts, a small ion will attain a velocity of about 30 cm./sec. and will traverse the distance between the plates in one-third of a second, while a

large ion will require 500 to 1,000 seconds to cover the same distance.

§ 3. Mechanism of the Formation and Destruction of Ions.

As has been mentioned, processes are continually at work everywhere in the air which result in the production of ions. Such ion-forming agents are known as ionisers. The intensity of an ioniser (ionising power) is determined by the number of pairs of ions per cubic centimetre per second, q, which it is able to produce. The state of ionisation existing in the atmosphere is brought about by the simultaneous action of many ionisers, though the processes are subject to large temporary variations at different places.

The constant action of these ionisers would cause a continuous increase in the number of ions present in unit volume were it not that processes are also at work which result in the diminution of their number.

Such processes may be divided into two groups, the first consisting of those processes which result in the actual destruction of ions; the second containing those which assist the removal of the ions from the body of the gas.

1. Destruction of ions :
    (a) Recombination with ions of opposite charge.
    (b) Combination [1] with larger uncharged particles (dust, water vapour, etc.), with consequent reduction of mobility.

2. Removal of ions :
    (a) Diffusion and adsorption.
    (b) Action of electrical forces (electrical convection).

The most important process leading to the disappear-

[1] To describe the combination of small ions with nuclei as a " destruction " of ions is really somewhat inconsequent, and opposed to what has been said above. This definition is, however, the customary one, and can be justified by the facts mentioned later.

ance of ionisation is the recombination of oppositely-charged ions. Whenever ions of opposite sign are present together in a gas there must exist a tendency to recombination, on account of electrostatic attraction ; it is probable that during such a process formerly complex molecular groups break up into single molecules. Recombination will obviously take place more often the greater the number of ions of each sign present in the gas. The calculation is, therefore, analogous to the Law of Mass Action of Guldberg and Waage, and the number of ions per second per cubic centimetre destroyed by recombination must thus be proportional to the numbers of both positive and negative ions present in unit volume, *i.e.*, equal to $\alpha \cdot n_+ \cdot n_-$, where α is the "coefficient of recombination" (of the dimensions cm.^{3} sec.$^{-1}$).

If, now, q pairs of ions per second per cubic centimetre are formed by the action of ionisers in unit time, the change in the number of ions present at any instant is given by the equation :

$$\frac{dn}{dt} = q - \alpha \cdot n^2,$$

when equal numbers of positive and negative ions are present. The simultaneous action of ionisation and recombination must, therefore, result in the establishment of a stationary state, where $\frac{dn}{dt} = 0$, and where the following relation exists between α, q and the number of ions :

$$n = \sqrt{\frac{q}{\alpha}}.$$

This equation has been found to be in agreement with experiment in all cases where the ions are not destroyed by any means other than the ordinary process of recombination (*cf.* § 26).

We will next consider the second of the processes

mentioned above—the combination of light ions with dust and condensation nuclei. Although in this case there is no actual diminution in the number of the ions, yet the small ions suffer so great a reduction in mobility that in many processes, *e.g.*, conduction of electricity in the atmosphere, they cease to play any important *rôle*. We have therefore considered this "fixation" also as a kind of destruction of the ions.

Ionic diffusion comes into play where there is a fall of ionic concentration in the gas, such as exists, for example, at the interface between the strongly ionised air within the soil and the relatively weakly ionised free air above the ground. At such interfaces a continuous passage of ions towards the region of lower concentration occurs.

Adsorption of ions takes place where an ionised gas comes in contact with the surface of a solid or liquid conductor. The inductive action of each individual ion on the surface near it causes a movement of the ion towards the surface, where it finally loses its charge and ceases to exist as an ion. This ionic adsorption is active only within an extremely thin layer next to the surface (about 0·1 mm.), and may in most cases be neglected.

Finally, it is also necessary to take into account the removal of ions by electrical forces; in many cases a very considerable diminution in the number of ions may result from this cause. In the free atmosphere this action is usually very small, since in a given volume of air the electrical convection brings in as many ions from neighbouring regions as it removes.

§ 4. Free Current and Saturation Current.

Let us consider two electrodes separated by air, which, as we know, is always feebly ionised. On applying a potential difference between the electrodes the ions begin to move towards one or other of the electrodes according to their sign, giving up their charges on reaching the plates:

a small current begins to flow.   This, however, produces a modification in the original distribution of ions.

So long as the electric field is very weak, the number of ions wandering in the convection stream may be neglected in comparison with the total number of ions present.   In other words, the number of ions per cubic centimetre ("ionic number") is practically unaltered, and the destruction of ions by recombination preponderates over the deposition on the electrodes by the convection current.

The current strength per unit cross-section (current density) is equal to the total quantity of electricity flowing per second through a surface of 1 sq. cm. placed perpendicular to the lines of force.   If n_+ and n_- are the numbers of positive and negative ions per cubic centimetre, e the charge on an ion (the elementary quantum of electricity), k_+ and k_- the mobilities of the two kinds of ion, and E the field strength, then the current density is given by

$$i = e(n_+ k_+ + n_- k_-)\text{E} \quad . \quad . \quad . \quad . \quad (1)$$

The expression

$$\Lambda = e(n_+ k_+ + n_- k_-) \quad . \quad . \quad . \quad . \quad (2)$$

is then called the specific electrical conductivity or the total conductivity of the air.   The quantity Λ may also be considered as consisting of two terms, λ_+ and λ_-, such that

$$\Lambda = \lambda_+ + \lambda_-, \quad \lambda_+ = e n_+ k_+, \quad \text{and} \quad \lambda_- = e n_- k_-.$$

λ_+ and λ_- are called the polar positive and negative conductivities.   The total conductivity is the sum of the two polar conductivities.

As long as equation (1) is fulfilled the current density is proportional to the applied potential difference ; that is to say, Ohm's Law is obeyed.   While this is the case the current is called "free current."   In the accompanying diagram this region is represented by the initial linear portion of the curve.

As the potential is still further increased more and

more ions will be drawn to the electrodes in unit time, and a marked diminution in the ionic concentration will occur. The conductivity of the gas will accordingly fall, and therefore the current density will no longer increase proportionally with the field strength, but more slowly. This phase corresponds to the part of the characteristic curve marked "Half-saturation Current." This portion of the curve is bent concavely towards the abscissa, while the first portion is a straight line whose inclination to the abscissa represents the value of the total conductivity
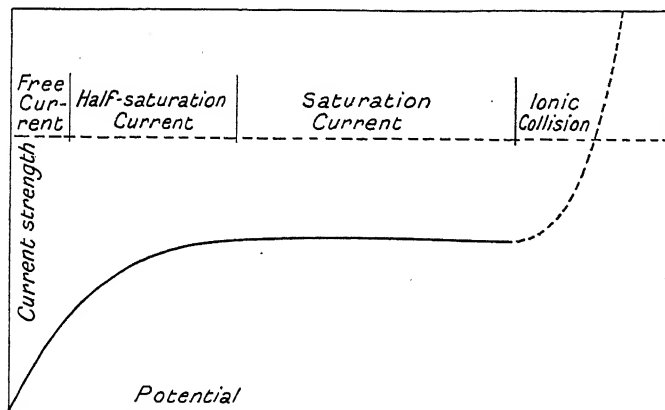
FIG. 1.—Current-potential curve in an ionised gas.

before it is influenced by the electric convection of the ions.

When the potential is raised still more, the removal of ions from a given element of volume by electrical convection at length outweighs the destruction of ions by recombination, while the number of ions (q) formed by the constant ionising agent remains always the same. A condition is thus finally reached in which practically all the ions produced in a second are drawn to the electrodes. The current strength in this case becomes

$$i_s = e \cdot q \cdot V,$$

and is equal to the total number of ions ($q \cdot V$) formed

per second in the gas space between the electrodes (volume V) multiplied by the elementary charge e. This current is known as the saturation current, and is characterised by the fact that further increase of potential produces no corresponding increase of current so long as no new factors affecting the ionisation come into play. In the characteristic curve this region is represented by the horizontal portion. The field strengths necessary for reaching this region vary very considerably with the particular experimental conditions, and with the nature and intensity of the ionising agent. In normal free air field strengths of 10 to 50 volts per centimetre usually suffice for the production of saturation current. Above these potential gradients the current ceases to rise.

No further alteration occurs until the potential is raised to quite extraordinary values, when a new secondary source of ionisation—ionisation by collision—comes into play. Thus, when the velocity imparted to the ions by the electric field exceeds a certain critical value, these swiftly-moving ions form, by collision with neutral gas molecules, new ions, which themselves attain a high velocity and thus form still more ions by collision. With high field strengths any further increase of potential causes an extraordinary increase of ionisation and current strength. This state of affairs is represented in Fig. 1 by the final dotted portion of the characteristic curve. In atmospheric electricity ionic collision only plays a part in such luminous phenomena as lightning, or St. Elmo's fire.

§ 5. The Electrical Conductivity of the Atmosphere.

As has been already mentioned, the groups of ions which exist in the air have mobilities of widely differing magnitudes, and the formulæ given on p. 12 for the polar and total conductivity are, therefore, not strictly applicable. If, for example, there are m groups of ions

of different mobilities $k_1 \ldots k_m$, and if in each group there are $n_1 \ldots n_m$ ions per cubic centimetre, then the rigid formulæ for the polar conductivities will have the form of summations of the following nature :—

$$\lambda_+ = \sum_{\nu=1}^{m} e \cdot n_\nu^+ \cdot k_\nu^+, \quad \lambda_- = \sum_{\nu=1}^{m} e \cdot n_\nu^- \cdot k_\nu^-.$$

Since, however, the small ions have on an average a mobility 1,000 times greater than the large ions, while the number of the latter is usually at the most only fifty times that of the former, it is evident that the terms corresponding with slow-moving ions in the above expressions have in general but little influence. For example, at the Eiffel Tower in Paris the number of large ions is fifty times the number of small ions (Langevin). If we put these values in the above formula, making due allowance for the small mobility of the large ions, we see that the effect of the latter on the conductivity is only one-twentieth, or 5 per cent. of that of the small ions. In country air, which is relatively free from nuclei, the part played by large ions is still smaller.

It is therefore permissible to use the equations given on p. 12 for approximate calculations of the total conductivity, using a mean value for k slightly less than the value for small ions.

From what has been said it is evident that the loss of charge of a conductor placed in free air must bear a definite relationship to the conductivity of the air at that particular place and time. We will now discuss this relationship, distinguishing between two cases, according as the surrounding air is still or in motion.

1. Still Air.—Let us consider a metallic conductor, *e.g.*, a metal ball, connected with an electroscope or electrometer and set up in a space of considerable volume containing still air—a room, for example. As soon as the

conductor is charged a current begins to flow from all
sides towards it, as can be seen quite clearly in a few
minutes from the fall in potential registered by the
electrometer. If the ball is charged, say, positively, then
negative ions move towards its surface, causing in the
neighbourhood an excess of ions of this sign while the
positive ions move away from it. In this way in the
neighbourhood of the surface of the conductor a free
space charge of opposite sign is formed, which causes a
distortion of the field in that region. The potential
gradient near the surface is considerably increased,
and consequently the velocity of the ions moving to-
wards the conductor is raised. The whole phenomenon,
which we may briefly describe as " electrode action,"
is of importance in many measurements of atmospheric
electricity.

The alteration in the distribution and velocity of the
ions and in the field strength near the body occasioned
by this electrode action greatly complicates the relation
between the loss of charge of the conductor and the
conductivity of the air. It has been proved by experiment
that the so-called dissipation law of Coulomb [1] is valid ;
according to this law, the loss of charge in unit time of a
conductor placed in still or moving air is proportional at
any moment to the charge still remaining :

$$\frac{d\mathrm{Q}}{dt} = a \cdot \mathrm{Q}.$$

The proportionality factor, a, differs, however, for still
and moving air, and in the latter case depends also on the
velocity of the air, when this is small.

With the aid of certain simplifying assumptions the
distortion of the field by " electrode action " may easily
be calculated for the case of still air,[2] and the relation

[1] C. A. Coulomb, *Mém. de l'Acad. Paris*, 1785, p. 616.
[2] J. J. Thomson, " Conduction of Electricity through Gases,"
2nd ed., Cambridge, 1906.

between the total conductivity and the empirical factor *a* obtained. This has, however, no practical value, since the case of completely still air is hardly ever met with in the free atmosphere, while even the smallest air currents nullify the assumptions and the applicability of the formula.

2. Air in Motion.—This case has been theoretically treated by E. Riecke.[1] If the wind velocity is sufficiently great, it may be assumed that no distortion of the field by excess ions in the neighbourhood of the conductor occurs, *i.e.,* that " electrode action " is prevented by the motion of the air. In this case the loss of charge per second of a positively-charged body is proportional to the negative polar conductivity, while the loss of a negatively-charged ball is proportional to the positive polar conductivity :

$$-\frac{dQ_+}{dt} = 4\pi \cdot \lambda_- \cdot Q_+ \text{ and } -\frac{dQ_-}{dt} = 4\pi \cdot \lambda_+ \cdot Q_-.$$

According to Riecke these formulæ hold good independently of the velocity of the air, as long as this is above a certain critical value. Extrapolation to the condition of still air is therefore not permissible. As Thomson (*loc. cit.*) has shown, the coefficient of dissipation in still air is proportional to the total conductivity, while in moving air it is simply equal to 4π times the polar conductivity.

Riecke's formula holds, as W. F. G. Swann showed, for any form of conductor, *e.g.*, for a stretched wire. The same author calculated, for this case, that air velocities less than 20 cm. per second are often insufficient to allow of the strict application of Riecke's formula. The exact value of the critical velocity depends on the special conditions of the experiment, and is not accurately known.

[1] *Ann. d. Phys.* (4), **12**, 52 (1903) ; *Gött. Nachr.*, 1903, pp. 1, 32, 38, 39.

§ 6. Measurements of the Coefficient of Dissipation in Air, and their Application to the Determination of the Conductivity.

As has been said, it was established by Coulomb that the loss of charge of a conductor is due for the most part to the conductivity of the air, small though this may be, and only to a very small extent to unavoidable faults of
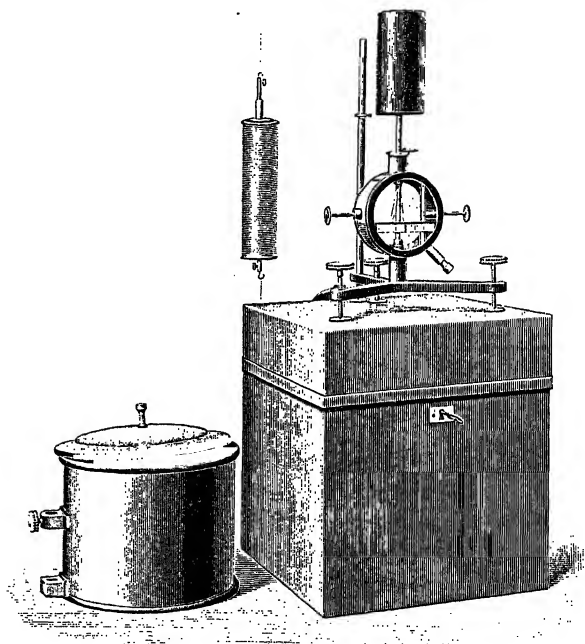
Fig. 2.—Elster and Geitel's dissipation apparatus.

insulation. The integral form of the dissipation law established by him, and mentioned on p. 16, is as follows :

$$Q_t = Q_o \cdot e^{-at} ;$$

from this it is seen that the coefficient a may be readily determined by measuring the charge at the beginning of an experiment, and again after t minutes.

The fallacy which persisted for almost a hundred years that damp air conducts better than dry was first dis-

proved experimentally by Linss (1887), who showed that the loss of charge in dry air is about 1 per cent. per minute, corresponding to a value of 0·01 for the coefficient a.

By the year 1900 such measurements had assumed a more general importance, owing to a better understanding of the mechanism of electrical conduction in air on the ionic theory. Since then numerous experiments on dissipation coefficients in the most various localities have been carried out by means of a portable instrument designed by the two German investigators, J. Elster and H. Geitel.[1]

A sketch of Elster and Geitel's apparatus is given above. It consists of an electroscope, to the leaves of which is connected, by means of a rod 6 cm. long, a dissipating body in the form of a closed and blackened cylinder 10 cm. high and 5 cm. wide. The system is protected from the disturbing influence of the electric field of the earth by means of another cylinder, open at the bottom, which is held in a clamp over the dissipating body. The actual potential measurements are four in number : the first two form the actual dissipation measurement, one reading being taken at the beginning and one at the end of the chosen time of observation ; the other two, as an insulation test, are made with the dissipating body removed. The loss through faulty insulation is usually so small that it amounts to less than 1 per cent. of the loss by dissipation. In cases where it is larger than this, a correction must be applied, and it is also necessary to take into account the increase in the capacity of the system caused by the dissipating body. Exact details of the carrying out of the measurements and of the calculation of the dissipation coefficients are given in special works on atmospheric electricity, a list of which is given at the end of this book.

[1] *Phys. Zeitschr.*, **1**, 11, 245 (1899) ; *Ann. d. Phys.* (4), **2**, 425 (1900).

Later investigations—those of H. Schering in particular —showed that the use of the protecting outer cylinder diminished to a great extent the value of the results obtained. Measurements made with such a cylinder are dependent to a high degree on wind relations, and on the flow of air in the space between the dissipating body and the protecting cylinder, and do not give a satisfactory measurement of the conductivity. When the electroscope is charged, as is usual, to 100 or 200 volts, a current of practically saturation value flows in this space, and therefore the loss of potential per minute is no longer proportional to the existing potential, but independent of it.

Further, besides the fact that the initial requirement of a conductivity measurement (free current according to Ohm's law) is not fulfilled, it will be impossible to obtain comparable results owing to changes in the flow of air with fluctuations of wind velocity. For these reasons the use of the protecting cylinder was soon abandoned, and the apparatus was used without it, being set up in places well protected from the earth's field, such as verandahs open at the side and protected above, porches, etc. With such arrangements, as E. Schweidler [1] has shown, an approximate measure of the polar conductivity may be obtained with Elster and Geitel's apparatus, or with others of equally simple construction. Exact proportionality with the polar conductivity cannot be hoped for, since the conditions of free current are only satisfied for that part of the dissipating body which projects above the neck of the electroscope. Accordingly, the greater the capacity of the dissipating body relative to that of the connecting rod, the better will be the proportionality between the dissipation and the conductivity. If the dissipating body is placed too near the

[1] *Wiener Ber.* (II.A), **115**, 1269 (1906); **118**, 91 (1909); **125**, 998 (1916).

case of the electroscope, free current is not obtained with certainty, and on this account (see below) later modifications were introduced in which the dissipating body is connected to the electroscope by a longer conductor of small capacity, *e.g.*, a thin wire.   E. Schweidler (*loc. cit.*) and others have made parallel measurements of the dissipation and the absolute polar conductivity, which they obtained by other methods, to be described later, and so obtained approximate reduction factors which enable the conductivity to be calculated from observed values of the dissipation coefficient.   A. Gockel,[1] later, used for dissipation measurements a Wulf double-string electrometer,[2] directly attached to a dissipating body consisting of a rod 50 cm. long and 5 mm. thick.   In this way the conditions of free current were satisfied over almost the whole length of the rod.

More exact, though less convenient, is the arrangement given by H. Schering.[3]   The dissipating body consists of a ball of 10 cm. diameter, or a cylindrical rod 25 cm. long and 1·5 cm. thick, which is suspended from a vulcanite insulator by means of a silk thread in a place shielded from the earth's field.   The body is connected to the electroscope by means of a very fine wire 60 cm. long. In this case the flow of electricity is almost entirely in the form of free current, the amount of saturated current in the electroscope itself being vanishingly small.

If K is the capacity of the dissipating body alone, (C + K) the capacity of dissipating body and electroscope together, and V the initial potential, then the loss of charge of the whole system per unit time amounts to $(C + K) . \dfrac{dV}{dt}$.   According to p. 17, this is equal to 4π

[1] A. Gockel, " Luftelektrizität " (Leipzig : Hirzel, 1908), p. 19.

[2] *Phys. Zeitschr.*, **8**, 246, 527 (1907).

[3] *Diss. Göttingen*, 1904 ; *Ann. d. Phys.* (4), **20**, 174 (1904).

times the product of the initial charge of the dissipating body alone, KV, and the polar conductivity $\lambda_{\mp}$. Thus

$$\lambda_{\mp} = -\frac{1}{4\pi} \cdot \frac{(C + K)}{K \cdot V_{\pm}} \cdot \frac{dV_{\pm}}{dt}.$$

In this expression the positive sign for λ corresponds to a negative charge on the dissipating body, and *vice versâ*, since it is always the ions of opposite sign which occasion the loss of charge of the body.

The same formula holds for the use of a later modification of Schering's apparatus,[1] in which the dissipating body takes the form of a stretched horizontal wire some 20 metres long connected with an electrometer, the wire itself being surrounded at a distance of 50 cm. with a concentric earthed shield of wide-meshed wire netting. This arrangement is particularly suitable for continuous recording with the aid of a mechanically registering quadrant electrometer, such as that of Benndorf.[2] When both the polar conductivities are to be recorded simultaneously, two similar suspended wire systems and electrometers are, of course, necessary. Such recording apparatus has been in continuous operation for a long time in various atmospheric electricity stations, such as Potsdam (Kähler), Teichof-Graz (Benndorf), Seeham (Schweidler) and Davos (Dorno).

W. F. G. Swann[3] has shown that in the Schering wire method too low results for the conductivity may occur even when care is taken to ensure free current. The action of the earth's field outside the earthed net produces, as a rule, a bound negative charge on the upper side of the latter, and when the air flowing past the net has a velocity lower than about 20 cm. per second this may cause a concentration of the ions near the net which is not in accordance with their undisturbed distribution. Thus,

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[1] *Göttinger Nachr.*, 1908, p. 201.

[2] H. Benndorf, *Phys. Zeitschr.*, **7**, 98 (1906).

[3] *Terr. Magn.*, **19**, 23–37 (1914).

with the net arrangement also, the apparatus must be set up in a place which is as little exposed to the earth's field as possible—under trees in a garden, for example. According to Kähler and H. Markgraf,[1] this is the case with the installation at the Potsdam Observatory.

The theory of the registration of the conductivity has been worked out by H. Benndorf.[2] The most suitable of the three possible methods is the following: The dissipating wire is automatically charged at regular intervals to a definite potential; it is then insulated, and the fall in potential under the influence of the ionised air is registered. The value calculated from observations over an interval (say, 10 minutes) is the average value, $\bar{\lambda}$, over the whole interval τ :

$$\bar{\lambda} = \frac{1}{\tau} \int_0^\tau \lambda dt,$$

where λ is the instantaneous value of the polar conductivity.

The results of the numerous dissipation measurements made between 1900 and 1910 will receive a brief mention later, together with those of the absolute conductivity measurements. Naturally the significance of older measurements with the apparatus of Elster and Geitel has diminished greatly since the introduction of more exact means of measurement or actual registration by Schering's wire method. The ill-defined results of measurements with a protecting cylinder must be left altogether out of consideration in the present work.

Elster and Geitel's apparatus, however, still finds occasional application, even at the present day, as a portable instrument, and, in conclusion, something may therefore be said as to the use of a reduction factor which allows of an approximate calculation of the polar conductivity from dissipation measurements.

[1] *Meteorol. Zeitschr.*, **28**, 202 (1911); **41**, 65 (1924).
[2] *Wiener Ber.* (II.A), **118**, 1192 (1909).

If the rate of discharge of the Elster and Geitel electro-scope, with the dissipating body, at a mean potential V, is expressed in volts per minute, then the polar conductivity in electrostatic units is, according to Schweidler,[1]

$$\lambda_\pm = - \, 4 \cdot 54 \, . \, 10^{-3} . \frac{1}{V_\mp} . \frac{dV_\mp}{dt}$$

§ 7. The Principles of Gerdien's Method for determining Conductivity (Aspiration Method), and its Improvement by Swann.

H. Gerdien [2] has developed a method for the determina-tion of atmospheric conductivity which avoids the chief sources of error of the methods described in the previous section (alteration of ionic distribution in the neighbour-hood of the charged body in still or slowly-moving air, *i.e.*, the effect which we have called " electrode action "). The method consists in drawing a constant stream of air by means of a fan through a cylindrical condenser whose outer electrode is earthed, and whose inner electrode is connected to a leaf electroscope (in the newer apparatus to a Wulf double-string electrometer) and charged to a moderate potential of the order of 100 volts.

It will be seen later that a method similar in principle can also be used for determining the number of ions per unit volume, and their mobility. J. Zeleny [3] was probably the first to use the method for the determination of ionic constants. It was described by him as the " method of perpendicular velocities," and was first used for measure-ments of mobility. H. Ebert has developed the same method for determining the number of ions per unit volume, and H. Gerdien, as already stated, has used it for measuring the absolute conductivity. Aspiration methods have, therefore, an outstanding importance in

[1] *Loc. cit.*, p. 20.

[2] *Phys. Zeitschr.*, **6**, 800 (1905) ; *Terr. Magn.*, **10**, 69 (1905).

[3] *Trans. Roy. Soc.*, A. **195**, 193 (1900).

atmospheric electrical investigations, and it is consequently necessary to consider the theory underlying them.

All these " aspirators " consist of a cylindrical condenser whose outer electrode (of radius r_a) forms the aspirator tube, and whose inner electrode is a relatively thin cylindrical rod (length l, radius r_i) placed axially within it. At one end of the tube is placed a small fan, which may be driven by hand or by a motor so as to draw air through the tube with a considerable velocity (up to 4 metres per second). Such an apparatus is shown in Fig. 3.

Let V be the potential difference between the two
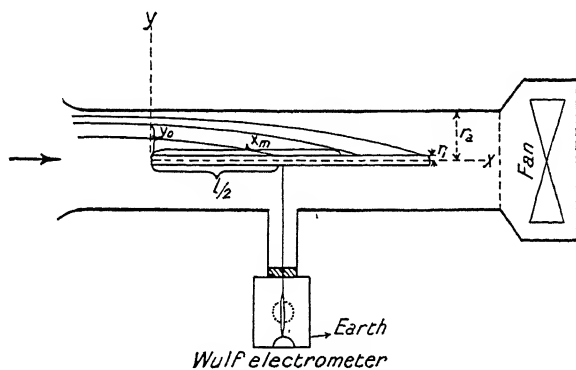
FIG. 3.—Gerdien's aspirator.

electrodes, G the velocity of the air stream, and r the distance of a given point inside the tube from the axis. Let the axis of the tube be taken as the x axis, the y axis being perpendicular to this. Then, according to the fundamental equations of electrostatics, the field strength at a given point within the condenser at a distance r from the inner electrode is

$$\frac{V}{r \log r_a/r_i}$$

If k is the mobility of the ions, which are carried along by the air stream in the direction of the x axis, they will

be attracted towards the electrode in a direction perpendicular to the air stream under the action of the electric field, and will therefore describe a parabolic path represented by the following equation :

$$y_o^2 - y^2 = \frac{2k\mathrm{V}}{\mathrm{G} \cdot \log r_a/r_i} \cdot x \quad . \quad . \quad . \quad . \quad (1)$$

In this equation y_o is the perpendicular distance from the axis of the point at which the ion under consideration enters the condenser ($x = 0$). By putting $y_o = r_a, y = r_i$, we obtain the maximum distance, x_m, along the inner electrode, at which ions are deposited :

$$x_m = \frac{\mathrm{G}(r_a^2 - r_i^2) \log r_a/r_i}{2k\mathrm{V}} \quad . \quad . \quad . \quad . \quad (2)$$

If k is the mean mobility of the ions of one sign, it is evident that for small values of V not all the ions in a given amount of air drawn through the condenser will reach the inner electrode (of length l), since x_m may be greater than l. The ions which reach the inner electrode, *i.e.*, whose parabolic paths all end on, and not beyond, the electrode, arise from a cylinder of air whose radius r_o may readily be calculated from the equation

$$l = \frac{\mathrm{G}(r_o^2 - r_i^2) \log r_a/r_i}{2k\mathrm{V}} \quad . \quad . \quad . \quad . \quad (3)$$

Now this cylinder of air, within which all the ions become attached to the oppositely-charged electrode, has a cross-section $r_o^2\pi$ and a length G (when the amount of air per second is considered). Its volume is therefore

$$\Phi = \frac{2\pi \cdot k \cdot \mathrm{V} \cdot l}{\log r_a/r_i} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

neglecting the small radius r^i in comparison with r_o. If the number of ions per cubic centimetre is n, then the total charge arriving at the inner electrode per second is $\Phi \cdot n \cdot e$, and this must be equal to the loss of charge per

second of the inner electrode plus electrometer (of total capacity C_1), so that

$$- C_1 . \frac{dV}{dt} = 4\pi . e . n . k . \frac{V . l}{2 \log r_a/r_i} \quad . \quad . \quad . \quad (5)$$

Therefore, if the observed potentials are V_1 and V_2 before and after the time of aspiration, T seconds (usually several minutes), it follows that

$$\frac{C_1}{T} . \log \frac{V_1}{V_2} = 4\pi . \lambda_\pm . \left(\frac{l}{2 \log r_a/r_i} \right) \quad . \quad . \quad . \quad (6)$$

Now the expression in the bracket in the last equation represents the well-known expression for the capacity of a portion of length l of an infinitely long cylindrical condenser. If we replace it by C'_2, we obtain the expression given by Gerdien for the polar conductivity of the ions opposite in sign to the charge on the inner electrode :

$$\lambda_\pm = \frac{C_1 . \log V_1/V_2}{4\pi C'_2 . T} \quad . \quad . \quad . \quad . \quad (7)$$

where V_1 and V_2 are the potentials observed before and after the period of aspiration T.

W. F. G. Swann [1] has since shown that this formula is not rigidly true, since it fails to take into account the distortion of the field inside the tube at the ends of the inner electrode, nor the influence of the supporting rod which connects the electrode to the electrometer. According-ing to him, the calculated capacity $C'_2 = \dfrac{l}{2 \log r_a/r_i}$ given above is to be replaced by C_2, the actual capacity, as determined experimentally, of that part of the apparatus which is exposed to the air stream (i.e., the inner electrode and support). The formula is then strictly true and takes the form

$$\lambda_\pm = \frac{1}{4\pi T} . \frac{C_1}{C_2} . \log \frac{V_1}{V_2} \quad . \quad . \quad . \quad . \quad (8)$$

[1] *Terr. Magn.*, **19**, 85 (1914).

The original apparatus of Gerdien had the following dimensions :—outer tube : length 56 cm., radius $r_a = 8$ cm.; inner electrode : length 25 cm., radius $r_i = 0.75$ cm. It has been shown experimentally by Hewlett [1] that for the above dimensions Swann's correction amounts to about 22 per cent., *i.e.*, calculations on the old formula of Gerdien are too small by this amount.

If absolute measurements of conductivity are to be made with Gerdien's aspiration apparatus, the air velocity must under all circumstances be so great that the ions are not completely removed from the air during their passage. For this to be the case the following inequality must be satisfied :

$$G > \frac{2k \cdot V \cdot l}{(r_a^2 - r_i^2) \cdot \log r_a/r_i} \quad \cdots \cdots \quad (9)$$

With the older form of Gerdien's apparatus, with hand-driven fan, one or two turns of the handle per second suffice to fulfil these conditions for initial potentials of about 100 volts.

As long as G is greater than the necessary value, the rate of discharge of the electroscope is proportional to the potential to which it is charged (see equation (5), p. 27). If, however, the potential is increased, or the air velocity decreased, so much that the conditions of formula (9) are no longer fulfilled, then all the ions in the aspirated air will be deposited on the inner electrode ; in these circumstances the observed rate of discharge is no longer proportional to the conductivity, but to the number of ions of the respective sign in unit volume of the air. It would, therefore, be possible to use the same aspiration apparatus also for ion counting. In order to be able to work with more suitable potentials it is, however, better to construct special apparatus with narrower tubes for ion counting (*cf.* below, § 9).

[1] *Terr. Magn.*, **19**, 231 (1914).

In carrying out conductivity measurements with the aspiration apparatus it is quite unnecessary to know the air velocity as long as care is taken that it is above the critical value in the above inequality. On the other hand, for ion counting it is essential to know the air velocity or the volume of air taken, and in apparatus constructed for this purpose anemometers are built into the tube itself. It must be remarked that for conductivity measurements it is quite unnecessary that the air velocity should be constant over the whole section of the tube for the final formula (8) to be strictly true (Swann [1]). According to Hewlett, in apparatus of the same dimensions as that of Gerdien, care should be taken not to make the initial potential higher than 60 volts. For this reason the use of fibre electrometers instead of leaf electroscopes is to be recommended, since the latter are very insensitive at these voltages. Fig. 4 shows the original form of Gerdien's apparatus, with leaf electroscope and hand-operated fan.

Gerdien's apparatus is best erected in places which are well protected from the earth's field, but which still allow sufficient access of free air, as, for example, under leafy trees, in porches, or in covered verandahs.

When a conducting body in electrical connection with the earth is set up at a point above the earth's surface, it then forms part of the earth, and the earth's charge consequently distributes itself over the body in accordance with its curvature. The same is, of course, true of any earthed apparatus exposed to the full influence of the earth's field.

The distortion of the field caused by the apparatus will be the more serious the higher the apparatus is raised above the ground and the greater the field strength, and, as Swann has pointed out, the distortion of the field (electrode action) will cause a change in the distribution

[1] *Terr. Magn.*, **19**, 209 (1914).

of the ions in the neighbourhood of the apparatus. With normally-directed potential gradients the bound charge on the upper side of the apparatus is negative ; in this case, therefore, the number of positive ions in the neighbourhood is increased, while the number of negative ions is diminished. Swann [1] has made a full theoretical investigation of the influence of this " electrode action " upon conductivity and ion-counting experiments. These investigations, together with the experiments of Hewlett,[2]
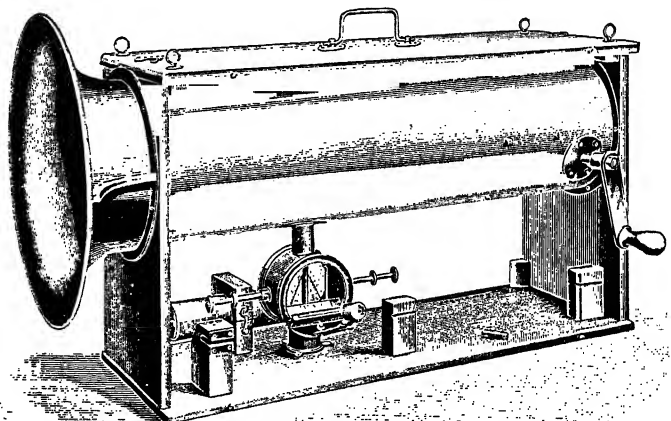
FIG. 4.—Gerdien's aspirator.

have shown that for low field strengths (100 volts per metre) the " electrode action " has no appreciable effect upon conductivity measurements, the same values for the polar conductivity being obtained whether the apparatus is exposed to the earth's field or not ; this is true for ions of both signs. Nevertheless, Hewlett recommends setting up the apparatus in places sheltered from the earth's field, since high field strengths may appear anywhere or at any time, and the electrode action will then become appreciable. For observations at permanent

[1] *Terr. Magn.*, **19,** 209 (1914).
[2] *Terr. Magn.*, **19,** 219 (1914).

stations it is best to install the apparatus in a large Faraday cage of wide-meshed network. A typical arrangement for work on board ship was designed by L. A. Bauer and W. F. G. Swann [1] for the experimental voyages of the Carnegie Institution of Washington. Swann [2] has also described a method for the automatic registration of conductivity by the aspiration method. A more detailed description of this arrangement will be given in a more complete general work on atmospheric electricity. [3]

K. Kurz [4] has drawn attention to a further possible source of error, both in conductivity and in ion-counting experiments. In the air there are always traces of radioactive substances, and some of these, such as the direct decomposition products (radium A, thorium A, and actinium A) of the emanations have the property of depositing themselves in an electric field on the negative electrode. Thus, when the inner electrode is negatively charged for the measurement of positive polar conductivity, it will collect more and more of these radioactive decomposition products as the time of aspiration is increased, and a high value for the conductivity will therefore be obtained. When the inner electrode is positively charged, the radioactive products will collect on the inner surface of the outer tube. It has been shown by experiment that this effect may be neglected in conductivity measurements with modern apparatus (fibre electrometer) when the time of aspiration necessary is short (less than five minutes). The case is otherwise with apparatus for permanent registration, where the action

[1] Publication No. 175 (Vol. III.), Carnegie Institution of Washington, D.C., pp. 382 *et seq.* (1917–18).

[2] Carnegie Institution of Washington, *Annual Report of the Director of the Department of Terr. Magn. for* 1917, p. 279.

[3] To be published by Friedr. Vieweg, Brunswick ; edited by Benndorf and Hess.

[4] *Phys. Zeitschr.*, **7**, 711 (1907) ; **9**, 177 (1908).

of this radioactive deposit increases from hour to hour, and it must then be taken into account by experimental determination of its action.

Finally, it should be remarked that the conductivity may also be obtained indirectly. There exists the following relation between i, the vertical electric current in the atmosphere, E, the potential gradient, and Λ, the total conductivity :

$$i = \Lambda \cdot E.$$

E and i may be simultaneously measured by direct methods, and from these values that of Λ may be calculated.

§ 8. Results of Observations of the Conductivity of the Atmosphere.

In the following table are given the mean values of conductivity measurements made in the most varied situations. The total conductivities as given are reckoned as the sum of the two polar conductivities. As a measure of the preponderance of ions of one or the other sign, the quotient

$$q_\lambda = \frac{\lambda_+}{\lambda_-}$$

is also given in most cases. As the table shows, q_λ is usually greater than 1 ; that is to say, λ_+ is greater than λ_-. Since k_+ is less than k_-, this corresponds to an excess of positive ions in the locality where the measurement was made. Conductivity measurements by all the methods described in the preceding pages are given in the table, since it was desirable to include results from the most varied places.

The values over land in Europe agree in general fairly closely with one another. The mean value of the total conductivity of the air in electrostatic units amounts to about 2.10^{-4} sec.$^{-1}$. According to the measurements of the Department of Terrestrial Magnetism, the mean

value over the continent of America is the same. Measurements in balloons and on mountain peaks show considerably higher values than those at sea level. On mountains the value of the quotient q_λ rises considerably above 1, which is readily explainable by the " electrode

MEAN VALUES OF THE TOTAL CONDUCTIVITY.

Author.	Place.	Year.	Λ in Electrostatic Units (sec.$^{-1}$).	q_λ.	Method.
E. v. Schweidler	Seeham (Salzburg) .	1908–20	$2.64.10^{-4}$	1·02	Dissipation apparatus.
C. Dorno . .	Davos (Switzerland) .	1910	2·8 ,,	1·13	Schering's method (regist.).
A. Gockel . .	Freiburg (Switzerland) .	1913–15	2·5 ,,	1·08	Dissipation apparatus.
,, . .	Eggishorn . . .	1915	8·5 ,,	1·33	,,
,, . .	Jungfrau Ridge . .	1915	6·0 ,,	1·42	,,
,, . .	Ice hole (Grindelwald) .	1915	0·09 ,,	—	,,
K. Kähler . .	Potsdam . . .	1910–11	0·95 ,,	1·16	Schering's method (regist.).
C. T. R. Wilson .	Peebles (Scotland) .	1908	1·1 ,,	—	Indirect.
A. Wegener .	Greenland (73° N. Lat.)	1907–8	5·5 ,,	1·28	Aspiration method.
K. W. F. Kohlrausch.	Porto Rico . .	1907–8	3·7 ,,	1·02	,,
G. Berndt .	Argentina . .	1912	2·6 ,,	1·02	Dissipation apparatus.
,, .	Amazon River . .	1914	0·68 ,,	0·97	,,
G. Angenheister.	Samoa . . .	1910	4·5 ,,	1·04	Aspiration method.
,, .	Suez Canal . .	1911	3·1 ,,	0·85	,,
H. Knoche .	Bolivia, 5,200 m.. .	1909	10·8 ,,	2·0	Indirect.
K. Hoffmann .	Spitzbergen .	1913–14	4·95 ,,	1·33	Schering's method.
A. Wigand .	Balloon at 9,000 m. .	1913–14	Up to ,, 26·0 ,,	Variable.	Aspiration method.
E. Kidson .	Atlantic Ocean . .	1909–10	3·4 ,,	1·16	,,
		1910–11	2·9 ,,	1·26	,,
S. J. Mauchly and L. A. Bauer.	Pacific Ocean . .	1921	3·09 ,,	1·15	,,
,,	,, (equatorial zone)	1921	3·01 ,,	1·18	,,
W. F. G. Swann .	New York–Hammerfest	1914	2·09 ,,	—	,,
,, .	Hammerfest Island .	1914	2·69 ,,	—	,,
E. Kidson .	Indian Ocean . .	1910	4·28 ,,	1·17	,,
C. W. Hewlett .	Pacific Ocean . .	1912–13	2·53 ,,	1·24	,,

action " of a raised mass of earth in the earth's field. The air at such places, therefore, contains an excess of positive ions.

The abundant material collected during the voyages of the experimental ship *Carnegie* in all seas shows quite clearly that the conductivity over the ocean,

far from being smaller, as might be expected from the smaller content of radioactive substances, is actually greater than over dry land ; this is the case even when the observations are made many thousands of miles from land.

The electrical conductivity is dependent both upon the number of ions and upon their mobility, and its behaviour is therefore very complex. The smaller amount of radio-active substances in the air over the sea may be more than balanced by the greater purity of the air and the consequently increased mean mobility of the ions. Very low values for the conductivity are obtained in damp places and in fog, as well as in clouds.

The changes in conductivity throughout the year have been measured in Davos, Freiburg (Switzerland), Potsdam, in Wärmland (Sweden), and in Spitzbergen. The observations in Central Europe all agree in showing a maximum in summer and a minimum in winter. In Potsdam the minimum is $0.70 . 10^{-4} \text{sec.}^{-1}$ (January), and the maximum $1.15 . 10^{-4}$ (July). In Davos, on the other hand, the maximum value is about twice as great as the minimum. In Spitzbergen the variation is considerably less than in Central Europe, and in higher latitudes the maximum appears to shift towards autumn.

As regards the daily variations, the numerous available observations show that the conductivity undergoes everywhere a regular daily change, which is in general dependent on the locality. The amplitude of the daily variation, like that of the yearly variation, differs very much in different places.

The daily variation exhibits marked local differences ; for instance, at Seeham (Salzburg) and Potsdam a double period is noticed, while elevated stations such as Davos have a simple daily variation (see Fig. 5). At almost all stations a principal maximum of conductivity occurs at three to four o'clock in the morning. After

sunrise the value falls considerably (formation of mist). In enclosed spaces also, such as cellars, where the temperature only varies slightly, a daily variation of conductivity occurs. Parallel observations of the number of condensation nuclei by W. Schlenck (Innsbruck) seem to show that daily variation in this number is the cause of the fluctuation of conductivity. The existence of a daily variation in cellars was definitely proved by Miss
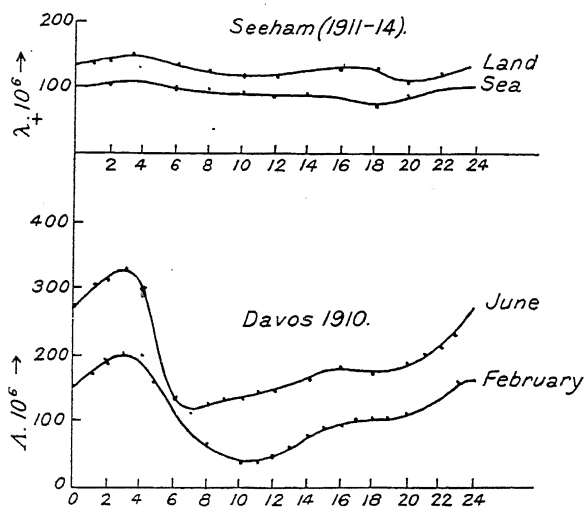
Fig. 5.—Daily variation of conductivity at Seeham and Davos.

Rose Stoppel [1] (Hamburg), who also found the same variation in high latitudes, as in Akureyri (Iceland) during the summer while the sun is permanently above the horizon. So far no satisfactory explanation of this phenomenon has been found.

Over the sea the daily variation, as the measurements on the *Carnegie* show, is different from that on land. The amplitude of the daily variation amounts to only 10 per cent. of the daily mean, and the average conductivity over the ocean is greater by day than by night.

[1] *Physikal Zeitschr.*, **27**, 755 (1926); also *Zeitschr. f. Botan.*, **12**, 529, 1920.

Of meteorological factors, the degree of purity of the air, as judged by the visibility, has the greatest effect upon the conductivity ; this is shown very clearly by a series of measurements extending over twelve years made by E. Schweidler [1] in Seeham (Salzburg). (Lower values of conductivity are accompanied by lesser degrees of visibility.)

The lowering of the conductivity by increase in the number of nuclei, as shown by A. Gockel,[2] is quite analogous and arises from the same cause. The lowest values are found by Gockel for damp mists ; the values in such cases may be from one-third to one-fifth of the normal. A high potential gradient is often accompanied by low values of conductivity, and *vice versâ*. As shown by the measurements of C. Dorno at Davos, B. Huber at Altdorf, and W. Schlenck at Innsbruck, the " Föhn " wind of the northern Alps, bringing very dry, pure air down into the valleys, causes a great increase in the conductivity. Relationship between temperature and conductivity is only noticeable in the mean values ; high temperatures correspond to slightly increased conductivity values on land or sea (Hewlett). The relation of conductivity to the relative humidity, barometric height and tendency, wind direction and force depends greatly on local conditions and is in any case extremely complicated. Markgraf [3] found by analysis of the Potsdam records that the general weather distribution influences the conductivity, areas of low pressure having a higher conductivity than regions of high pressure or transition areas.

In the Alps and the neighbouring regions increased conductivity has been noted by several authors on the mornings of thundery days, and the prediction of thunder-

[1] *Jahrb. f. Rad. u. Elektr.*, **18**, 1 (1921).

[2] *Neue Denkschr. Schweiz. Naturforsch. Ges.*. **54**, Abh. No. 1 (1917).

[3] *Meteorol. Zeitschr.*, **41**, 165 (1924).

storms several hours before their arrival has thus been made possible (Gockel). This rise of conductivity, on the other hand, does not occur in other places—for example, the North German Lowlands (Budig, Markgraf).

As regards the influence of solar eclipses on the conductivity and the dissipation of electricity in the atmosphere, the observations made up to 1918 have given quite contradictory results.

The Department of Terrestrial Magnetism in Washington sent out three expeditions,[1] in 1918, 1919 and 1923, to Lakin (Kansas), Sobral (Brazil) and Point Loma (San Diego, California) respectively. By the use of modern aspiration apparatus, with a measuring interval of only two minutes, concordant results were obtained in spite of the very different meteorological conditions.

During the first of the eclipses observations were made with a clear sky ; at Sobral the sky was cloudy, while at Point Loma there was a very light mist overhead. It had been assumed that the influence of the darkening of the sun on the electrical conditions would be of an indirect nature only, and that fall of temperature during the period of totality would play the chief part. This assumption is entirely contradicted by the results of the three expeditions mentioned. In all three eclipses a considerable rise of both polar conductivities was found during totality, while the change of temperature during the second and third eclipse was very small on account of the clouded sky. No explanation for this rise of the conductivities has yet been found.

A question of great interest is the behaviour of the conductivity values with increasing elevation in the atmosphere. The great increase in conductivity during balloon ascents to 6,000 metres was demonstrated by

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[1] L. A. Bauer, H. W. Fisk, S. J. Mauchly, *Terr. Magn.*, **24,** 87 (1919) ; S. J. Mauchly and A. Thomson, *ibid.*, **25,** 41 (1920) ; H. F. Johnston, *ibid.*, **29,** 13 (1924).

H. Gerdien with his aspiration apparatus. A. Wigand [1] has extended these measurements to about 9 km. by a series of ascents. The total conductivity, amounting to only about 1.10^{-4} sec.$^{-1}$ in the neighbourhood of the starting point (Bitterfeld), rose to three times this value at a height of 3 km., to ten times at 6 km., and then with increased rapidity to 16 to 27.10^{-4} at 9 km. Cloud and fog layers may cause local diminution of the values. The increased rise above 6 km. shows that the stratosphere, whose upper layers will probably never be accessible to man, must possess an enormously increased conductivity. This upper shell of air ("Heaviside layer" [2]), in conjunction with the conducting surface of the earth, seems to play a special part in the transmission of the electric waves of wireless telegraphy and telephony (cf. § 28).

It is not difficult to find reasons for the rapid increase of conductivity with height. As will be shown later, the ionisation itself increases with the height, and in addition to this the ionic mobility must increase owing to the diminution in the pressure and in the number of nuclei. Conductivity measurements in the upper layers by night would be of the utmost value in finding a reason for the strong ionisation at great heights, but unfortunately they are not available.

[1] *Verh. d. D. Phys. Ges.*, **16**, 232 (1914) ; *Terr. Magn.*, **19**, 93 (1914) ; *Abh. d. Naturf. Ges. Halle*, New Series, No. 4, 1914 ; *Ann. d. Phys.* (4), **66**, 81 (1921).

[2] Since A. E. Kennelly (*Electr. World and Engineer*, New York, March 15th, 1902) drew attention to the existence of such a layer even before Heaviside (*Encyclop. Brit.*, **33**, 10th ed., December, 1902), it has been proposed to adopt for it the name Kennelly-Heaviside layer (see McAdie, *Science*, **51**, 540 (1925)). C. *Chree* however (*Nature*, **119**, 82 (1927)) showed that as early as in 1883 Belfour *Stewart* in his article on Terrestrial Magnetism, § 121 and § 134 in the Ninth Edition of Encyclopædia Britannica, has advanced the idea of the existence of a well conducting layer in the upper atmosphere. So in fact the priority of this author cannot be doubted. The term "Heaviside layer" is, however, generally in use and we cannot but adopt it.

§ 9. Ion Counting—Theoretical Principles, Apparatus and Sources of Error.

(a) **Theory of Ebert's Aspirator (Ion Counter).**—In the expression for the polar conductivity the number of ions (n) and the mobility (k) occur only in the form of a product, and the two quantities are not known separately ; the measurement of the conductivity alone is therefore insufficient for the determination of the state of ionisation at the time. Special methods have, therefore, been worked out for the determination of the number and average mobility of both the principal groups of ions.

The first of these, described by H. Ebert,[1] was an aspiration apparatus designed for the determination of the number of small (mobile) ions in unit volume ; it is usually known as Ebert's ion counter. The theory of this apparatus has already been discussed in connection with Gerdien's apparatus. The two are identical in principle, and Ebert's apparatus differs from the former only in the dimensions of the tubes, the air velocity (G), and the potential of the inner electrode (V). These values are so chosen that all the small ions of one sign present in the air drawn through the apparatus are deposited on the electrode. This is the case when the air velocity satisfies the condition that

$$G \leqq \frac{2k \cdot l \cdot V}{(r_a^2 - r_i^2) \log r_a/r_i}.$$

When this is the case, increase of the potential causes no increase in the loss of charge per unit time.

Now if the volume of air in cubic centimetres drawn through the aspirator per second is $W = r_a^2 \cdot \pi \cdot G$, and if the potential falls from V to V' volts in t seconds, then

$$W \cdot n \cdot e \cdot t = \frac{C}{300} (V - V'),$$

since the loss of charge of the electroscope plus condenser

[1] *Phys. Zeitschr.*, **2**, 662 ; *Arch. de Genève*, **12**, 97 (1901); *Verh. d. D. Phys. Ges.*, **7**, 2, 34 (1905).

(total capacity C) is equal to the opposite charge on the ions arriving in the same time. The division by 300 gives the potential values in electrostatic units. The formula, therefore, allows the calculation of $n.e$, the product of the number of ions per cubic centimetre and the elementary charge ; of course, one measurement must be made with a positive, and another with a negative, charge on the inner electrode. Division by e then gives the required ionic number n. The loss of charge per second, $(V-V')/t$ should also be measured with the fan stopped and the tube closed, and subtracted from the first value, but as a rule this correction is quite negligible.

With the older forms of Ebert's apparatus, with an outer tube 30 cm. long, 3 cm. wide and an Elster and Geitel leaf electroscope, an aspiration time of at least fifteen minutes was necessary. By the use of apparatus of larger volume fitted with more sensitive thread electrometers this time has been reduced to two to five minutes. The fan is usually worked by a clockwork motor, and the air velocity is not allowed to exceed 2 metres per second. In more recent forms of the apparatus the aspiration tube is vertical ; this has the advantage of minimising trouble due to the drawing in of insects. For the same purpose, a blunt conical cap is also attached to the upper opening of the tube (see Fig. 6, p. 41). The dimensions of the modern apparatus are such that with a potential of 200 volts on the inner electrode ions of mobilities down to 0·03 cm./ sec. : volt/cm. are caught. A portion of the intermediate and heavy ions are under these circumstances also captured, and this must be taken into account in the consideration of the results. Especially is this the case where the number of heavy ions is likely to be large. It is then advisable to carry out parallel measurements with a short (10 cm.) tube in which the lower limit of mobility of the deposited ions has a value of 0·2 cm./sec. : volt/cm.

(b) **Sources of Error in Ion Counting, and Standards for**

the Setting up of the Apparatus.—In addition to the source of uncertainty just mentioned, which chiefly occurs in the presence of a very large number of heavy ions, two other possible sources of error must be taken into account : (1) the influence of the deposition of radioactive substances during the aspiration, and (2) the influence of the earth's field on apparatus set up in the open.

As regards the first effect, it has been shown by Kurz
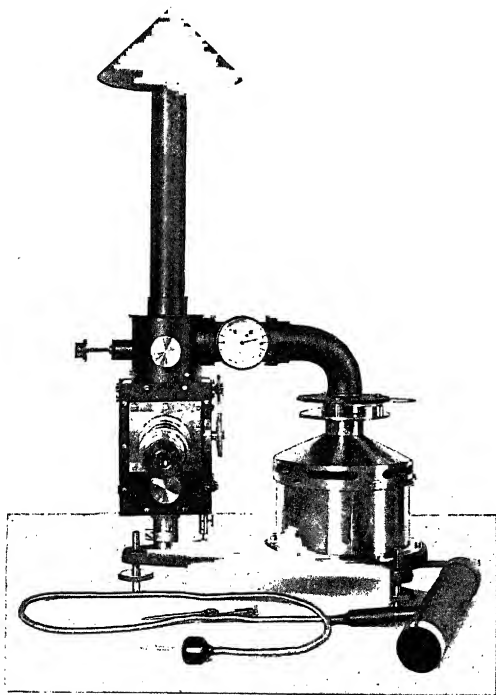
FIG. 6.—Ebert's ion counter with Wulf electrometer.
(Günther and Tegetmeyer, Brunswick.)

(*loc. cit.*, p. 31) that such radioactive deposits may raise the ion number obtained with the older forms of Ebert's apparatus by several per cent. In the more recent forms, in which the time of aspiration is only a few minutes, this effect may be entirely neglected.

The remarks as to the influence of the earth's field on apparatus exposed to it ('' electrode action '') which were made in dealing with Gerdien's conductivity measurements naturally hold as well for the ion counter. Here also W. F. G. Swann [1] was the first to study the effect from the theoretical and experimental standpoints. He came to the conclusion that with a normally-directed field the electrode action may cause the value obtained for the negative ion number to be very considerably below the true value. Later investigations by H. Norinder [2] and J. F. Mackell [3] have shown that the effect is also noticeable with an Ebert aspirator with a protecting cap over the mouth of the tube. For field strengths from 30 to 120 volts per metre the value of n_- may be from 17 to 27 per cent. too small. Some experiments made at Kew Observatory by E. H. *Nichols* [4] did, however, not confirm Swann's conclusions.

The conclusion to be drawn from all these investigations is that Ebert's ion counter must be erected in such a way that the influence of the earth's field is completely removed ; this precaution is equally necessary when the mouth of the tube is capped. For measurements in the open the whole apparatus must be surrounded by an earthed wide-meshed wire cage, projecting sufficiently far above the opening of the tube.

It must not be forgotten that, apart from the effect on the apparatus itself, the earth's field naturally affects the distribution of the ions near the surface, causing a preponderance of positive ions near the ground. In completely still air, however, this effect should quite disappear at a height of 20 metres (Schweidler [5]). Swann [6]

[1] *Terr. Magn.*, **18**, 163 ; **19**, 205 (1913–14) ; *Phys. Rev.*, **21**, 449 (1921).
[2] *Arkiv. f. Mat., Astron. och Fysik*, **15**, No. 2, Stockholm, 1920.
[3] *Phys. Rev.* (2), **21**, 436 (1921) ; **17**, 390 (1919).
[4] *Terr. Magn.* **21**, 87 (1916).
[5] *Wiener Ber.* (II.A), **117**, 623 (1908).
[6] *Terr. Magn.*, **22**, 1124 (1917).

has recommended that measurements should be made on a tower at least 15 metres high, the apparatus being also protected from the earth's field. The breeze which is almost always to be found at this height will then hinder the formation of strongly unipolar layers. As a matter of fact, A. Gockel found under these conditions a value for $q = n_+/n_-$ very near unity.

(c) **Improvements in Apparatus.**—In the original apparatus of Ebert the determination of the aspirated air volume was attended by considerable difficulty. For this reason a Rosenmüller anemometer is built directly into the aspiration tube behind the electrode in the ion counters constructed by Günther and Tegetmeyer (Brunswick), and Edelmann & Son (Munich). The former instrument is provided with a Wulf bifilar electrometer ; the latter with the single-fibre electrometer of Lutz.[1] In the latter a variable condenser is also provided, so that the electrometer is only used as a null instrument.

A still more sensitive and improved type of ion counter has been described by W. F. G. Swann.[2] Special arrangements for the measurement of ion numbers in flying machines have been devised by A. Wigand and H. Koppe.[3]

Apparatus for the automatic registration of ion numbers has been constructed by C. Nordmann,[4] and also by P. Langevin and M. Moulin.[5]

§ 10. Results of Ion-Counting Experiments.

Since a certain number of heavy ions are deposited in the ion aspirator together with the light ions, the figure given by most observers as the number of the latter is a little too high. This is also partially true of the measurements

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[1] *Münchener Sitz.-Ber.*, 1909, 14 Abh.

[2] *Terr. Magn.*, **19**, 171 (1914).

[3] *Naturwissensch.*, **7**, 487 (1919) ; *Mitt. d. Naturf. Ges. Halle*, **6**, 3–14 (1921).

[4] *Compt. Rend.*, **138**, 1418, 1596 (1904) ; **140**, 430 ; **141**, 945 (1905).

[5] *Compt. Rend.*, **140**, 305 (1905) ; *Bull. Soc. Franc.*, 1907, p. 264 ; *Le Radium*, **4**, 218 (1907).

collected in the following table. For land stations with pure air, however, and for measurements over the sea, the discrepancy may be neglected ; in any case, it can only be calculated when the number of heavy ions has also been measured (*cf.* § 13).

In the table the value of the product of the ion number per cubic metre and the ionic charge ($10^6 . n_+ . e$ and $10^6 . n_- . e$ respectively) is given. This value, also called the "ionic content," is represented by E_+ and E_-.

The figures obtained for the ionic contents $E_\pm$ are

Author.	Place.	E+	E−	q_E
Lüdeling (1901) . . .	Heligoland . . .	0·25	0·13	1·92
,, (1904) . . .	Potsdam	0·37	0·30	1·23
Simpson (1904) . . .	Lapland . . .	0·38	0·33	1·15
Gockel (1904–5) . .	Freiburg (Switzerland) .	0·34	0·25	1·36
Ebert (1905) . . .	Munich . . .	0·53	0·42	1·26
,, (1905) . . .	Barcelona . . .	0·30	0·23	1·28
,, (1905) . . .	Gulf of Lyons . .	0·19	0·18	1·06
Linke (1906) . . .	Pacific Ocean . .	0·20	0·20	1·00
Eve (1907) . . .	Atlantic Ocean . .	0·33	0·27	1·24
Pacini (1908) . . .	Mediterranean . .	0·43	0·28	1·52
A. Wagner (1910) . .	Hungary (Lowlands) .	0·52	0·40	1·30
Dorno (1910) . . .	Davos . . .	0·59	0·48	1·23
Knoche (1909) . .	Bolivian Cordillera .	1·12	0·96	1·17
Hess and Sensel (1910) .	Danube Plains, Vienna .	0·38	0·34	1·12
Simpson and Wright (1911) .	Atlantic Ocean . .	0·37	0·31	1·19
Berndt (1911–12) . .	,, ,, . .	0·32	0·30	1·07
,, (1911–12) . .	Buenos Aires . .	0·34	0·32	1·06
Dobson (1909–12) . .	Kew (England) . .	0·21	0·15	1·40
Kohlrausch (1912–13) . .	Seeham (Salzburg) .	0·31	0·30	1·03
Berndt (1914) . .	Amazon River . .	0·18	0·17	1·06
,, (1913–14) . .	Atlantic Ocean . .	0·27	0·29	0·93
Knoche (1912) . .	Easter Island (Pacific Ocean)	0·48	0·48	1·00
Buchheim and Dember .	Peak of Teneriffe . .	0·78	0·38	2·05
Wright and Smith (1914) .	Manila (Philippines) .	0·20	0·18	1·11
,, ,, (1914)	Mount Paral (2,400 m.) .	0·58	0·37	1·57
L. A. Bauer, Fleming and others	Pacific Ocean . .	0·37	0·31	1·22
Gockel (1913–15) . .	Freiburg (Switzerland) .	0·48	0·43	1·11
,, (1915–16) . .	Klein Scheidegg (2,100 m.) .	0·68	0·50	1·36
,, (1915–16) . .	Jungfrau Ridge (3,700 m.) .	0·72	0·42	1·71
,, (1915–16) . .	Aletsch Glacier . .	1·37	0·87	1·58
A. Riegl (1909–11) . .	Hungary (Lowlands) .	0·46	0·43	1·07
Bauer and Swann (1916) .	Sub-Antarctic Ocean .	0·36	0·30	1·22
A. Gockel (1911) . .	Balloon (4,000–4,500 m.) .	0·46	0·47	0·98
A. Wigand (1919) . .	Flying machine (5,200 m.) .	1·14	0·94	1·23

naturally independent from the value assumed for the ionic charge, while the ion numbers themselves depend on this value. If, for example, this is taken as $4·77 . 10^{-10}$ electrostatic units, then a value of $E_\pm = 0·40$ ESU/cu.m. corresponds to an ion number of 838 per cubic centimetre, a value $E_\pm = 0·20$ to an ion number of 419 per cubic

centimetre. The quotient $q_E = {E_+}/{E_-}$ gives a measure of the unipolarity, while the difference $E_+ - E_-$ corresponds to the excess of free positive charge per cubic metre. It is apparent from the foregoing table that the ionic content is subject to smaller variations than the conductivity. The positive ionic content is larger than the negative almost everywhere, even over the sea.

The values over dry land in all latitudes are not much greater than those over the sea; this was clearly established by the numerous measurements in all waters made during the voyages of the experimental ship of the Carnegie Institution [1] giving an average of $n_+ = 615, n_- = 499$. Measurements on mountain peaks and in flying machines all show a very great increase in the ionic content with height, and on mountains the unipolarity is very strongly marked. The behaviour of ionic content over the ocean is the more noteworthy, since there, as will be seen later, the chief sources of ionisation over land, the radioactive substances, are almost entirely absent. The subject will be discussed in connection with the balance of ionisation (§ 27).

The ionic content, like the conductivity, shows regular yearly and daily variations. In both hemispheres the minimum of ionic content falls in the winter months, and the maximum in the warm part of the year. The minimum coincides, according to Gockel, with the period of maximum snow. The daily variation is not so regular and differs very much with locality. Many observers find a double daily period : the maxima occur during the first hours of morning and afternoon, the minima in the late morning and in the evening. The results of the *Carnegie* expedition show a simpler daily variation over the sea, of very small amplitude : the figures by day are somewhat higher than by night. Over dry land also the daily

[1] S. J. Mauchly, Publication No. 175, Vol. v., Carnegie Inst. of Washington, p. 411.

variation of the ionic content is less than that of conductivity.

Those meteorological factors which have a strong influence on the conductivity have a similar influence on the ionic content. Thus all observers find a high ionic content on days when the visibility is high. There is also an undoubted connection with temperature. This connection is perhaps most clearly seen from the measurements of Simpson in Lapland. According to most observers, however, there is an inverse relationship between ionic content and relative humidity, rising humidity corresponding to lower ionic content.

The connection with the height and tendency of the barometer varies from place to place, and is in any case complicated by other factors. Large ions are formed by the agglomeration of small ions on condensation nuclei, and it is therefore to be expected that the number of small ions should diminish with an increase in the number of dust nuclei. This was very well shown by A. Gockel and others. In the Alps the " Föhn " wind brings about a very considerable increase in the ion number (Dorno, Huber, Gockel), which may well be ascribed to the descent of the pure, nucleus-free mountain air. On the other hand, layers of fog cause a decrease in the ion number.

A slight reduction in the ion number is usually produced by snow and gentle rain. Heavier rain often causes a considerable increase in the negative ion number, since negative ions are formed to a preponderating extent by the splashing of the drops (Lenard effect). The influence of the wind direction differs very greatly with the locality ; but it has been generally established that a rise of ion number occurs with increasing wind force, due to the fact that strongly ionised air is drawn into the atmosphere from the capillaries of the soil by wind suction. Furthermore, there is a very close parallelism between the ionic

content and the amount of radioactive substances present in the air (Hess and v. Sensel [1]).

As to extra-terrestrial influences, the following remarks may be made. During the passage of the earth through the tail of Halley's comet (1910) a temporary rise in the ion number was noted at three out of five stations, while at the other two no change could be detected. The very numerous observations which have been made during eclipses of the sun have given rather conflicting results. The majority of observers have recorded a decrease in the ionic content during the period of totality, but the results cannot by any means be regarded as certain. Whatever influence the eclipse may have upon the ionic content, it is certainly less than the effect upon conductivity, and this fact is in agreement with the observation of most investigators that a marked change in the average mobility occurs during the eclipse.

Observations on mountains and in flying machines agree in showing a rapid increase of ionic content with height (see table). This was at first ascribed to a direct ionising action of sunlight. Apart, however, from the fact that Wright and Smith,[2] during observations on Mount Pauai (2,460 metres) in the tropics, found no difference in the ionic content in direct sunlight and in the shade, it is quite definitely established by experiment that the spectral region active in producing ionisation cannot penetrate to the troposphere, since the solar spectrum at a height of 9 km. ends at $\lambda = 290 \, \mu\mu$ (Miethe and Lehmann,[3] Wigand [4]).

The increase of ionic content with height may be explained by the increased activity of an ionising agency which also plays a part at the surface of the earth, namely, the penetrating radiation known as ultra-gamma

[1] *Wiener Ber.* (II.A), **120**, 139 (1911).

[2] *Phys. Rev.* (2), **7**, 19 (1916).

[3] *Sitz.-Ber. d. Kgl. Preuss. Akad. d. Wiss.*, VIII. (1900).

[4] *Verh. d. D. Phys. Ges.*, **15**, 1090 ; *Phys. Zeitschr.*, **14**, 1144 (1913).

radiation (*höhenstrahlung*) (*cf.* § 23 (6)).   The decrease in the number of dust nuclei with height must also be taken into account, since this results in a diminution in the proportion of large to small ions.

§ 11. Measurement of the Average Mobility of the Ions.

Many exact methods are available for the measurement of the velocity of gas ions in an electric field ; the majority of these are, however, only applicable in the case of artificially ionised gases.   The conditions are considerably more complicated in atmospheric air, and the very weak natural ionisation of the air in itself renders the carrying out of such measurements considerably more difficult. Furthermore, it is necessary to take into account the number of heavy and intermediate ions present in the air, and these vary both with the dust and water-vapour content.

In free air there are thus ions of very different mobility present together.   Since in general only portable apparatus can be used for measurements in the open, it is customary to determine the average ionic mobility $\bar{k}$, as defined by the following expression :

$$\bar{k}_{\pm} = \frac{n_1 k_1 + n_2 k_2 + \ldots \ldots + n_m k_m}{n_1 + n_2 + \ldots \ldots \ldots + n_m}$$

In this formula $n_1 \ldots n_m$ represent the ion numbers per cubic centimetre of the ions of various mobilities. The formula can, of course, be used for the positive and the negative average mobility.

In artificially-ionised, carefully dried and dust-free air the mobilities, expressed in cm./sec. : volt/cm., amount to about 1·9 and 1·4 for the negative and positive ions respectively.   These numbers, of course, represent the mobilities of the light ions.

Suitable methods for determining the average mobility in the open air have been worked out by H. Gerdien [1] and H. Mache.[2]

[1] *Phys. Zeitschr.*, **4**, 632 (1903) ; *Göttinger Nachr.*, 1903, p. 383.
[2] *Phys. Zeitschr.*, **4**, 717 (1903).

If a stream of air carrying ions is drawn through a cylindrical condenser, the formulæ already developed (§ 7) serve for the calculation of the ions deposited on the inner axial electrode.

(a) **Gerdien's Apparatus.**—In this two coaxial cylindrical condensers, one behind the other, are used. A stream of air flowing with known velocity loses a measurable amount of its ions in the first condenser, between whose plates there is a suitably weak field (conditions for conductivity measurement); the rest are captured in the second condenser with a sufficiently strong field. Both the inner electrodes are connected to electrometers. The sum of the charges lost in the two electrometers gives, therefore, as in the ordinary ion counter, a figure proportional to the ionic content, while the loss in the first condenser alone is proportional to the polar conductivity of the sign in question. The quotient of the two values

$$\lambda = \sum_{\nu = 1}^{m} n_\nu \,.\, k_\nu \,.\, e \text{ and } \mathrm{E} = \sum_{\nu = 1}^{m} n_\nu \,.\, e \text{ is then the average}$$

ionic mobility, as defined above.

(b) **Mache's Apparatus.**—This depends on the same principle, but is of wider application, since it makes use of an ordinary Ebert ion counter with a simple attachment (additional condenser).

The condenser attachment consists of a tube of the same width as the outer tube of the Ebert apparatus, containing an axially placed rod which is maintained at a known low potential (3 to 15 volts) by means of a small battery. As in Gerdien's apparatus, a fraction only of the ions in the air stream is removed in the first condenser. Determination of the average mobility with this apparatus requires two successive measurements : (1) determination of the loss of charge E' in the Ebert apparatus with auxiliary condenser, and (2) measurement of the normal ionic content E with the auxiliary condenser earthed.

The mobility k is then calculated from the formula $k = C \cdot \dfrac{E - E'}{E}$, C being a constant depending on the aspirated volume of air per second, potential of the auxiliary condenser, etc. It is naturally assumed that the ionic content of the air does not alter during the time of measurement.

The objection raised by W. F. G. Swann,[1] already mentioned in § 7, to the use of the calculated value of the capacity of a cylindrical condenser placed in an ionised air stream instead of the experimentally measured value applies in this case also, and a correction must be applied to the formulæ given by Gerdien and Mache for the average mobility. The magnitude of the discrepancy has not been determined by experiment, but it should be the same as in conductivity measurements (p. 28). Unfortunately, almost all the mobility values which have been measured so far have been obtained with the uncorrected formula, and subsequent recalculation is impossible owing to lack of data as to the capacity values of the particular apparatus used. The corrected formulæ will be developed in a complete work on atmospheric electricity (Benndorf and Hess; cf. footnote 3, p. 31).

Measurement of the average mobility of the ions of both signs needs four successive measurements with Mache's arrangement, provided that an Ebert aspirator is available. Two ion counts are at the same time obtained. Gerdien's method gives, in addition, two direct values for the polar conductivity, since in this arrangement the first condenser is also connected to an electrometer. Careful tests of Mache's method by K. W. F. Kohlrausch [2] have shown, among other things, that it is necessary to raise the air velocity to at least $2\frac{1}{2}$ metres/sec.

[1] *Terr. Magn.*, **19**, 175 (1914).
[2] *Wiener Ber.* (II.A), **123**, 1929 (1914).

in order to diminish the influence of ionic diffusion in the tube to a negligible value.

§ 12. Results of Measurements of the Average Mobility.

Measurements carried out by the method of Gerdien and Mache have shown that the average mobility of the ions in free air is of the same order of magnitude (though somewhat smaller) as that of the small ions in laboratory experiments with air carefully dried and freed from dust (*cf.* p. 48).

The most important results are collected in the following table. On account of the capacity correction of Swann, details for the determination of which are lacking, the values which are obtained from older experiments by direct methods (Mache, Gerdien) are about 20 per cent. too high. The table also gives values for the average mobility obtained indirectly, *i.e.*, as the quotient of the observed average polar conductivity and the observed mean ion number at the station in question.

It will be seen that the average mobility in the open air at various places differs very little ; the mean value is about 1 cm./sec. : volt/cm. Over land k_- is usually a little larger than k_+, while over the sea the difference is negligibly small. The absolute value over the sea (1·3) is, however, higher than that over land, which is no doubt due to the smaller number of large ions in sea air.

Increased values for the mobility are observed at greater heights. On theoretical grounds it is to be expected that the ionic mobility should be inversely proportional to the atmospheric pressure. Owing to the small number of balloon observations and the often quite irregular decrease in the number of *condensation* nuclei with increasing altitude, it cannot be hoped to find this law confirmed by the measurements performed so far.

As regards the influence of meteorological factors on the average mobility, the humidity has been the most

Author.	Place and Date.	k_+	k_-	Method.
Gerdien	Göttingen, 1903	1·36	1·63	Direct.
Mache and Schweidler	Seewalchen (Austria), 1904	1·02	1·25	,,
Elster, Geitel, Harms	Palma (Mallorca), 1905	0·83	0·90	,,
Gockel	Freiburg (Switzerland), 1907	0·9–1·2	1·0–1·3	,,
Berndt	1915–16	0·94	0·97	Indirect.
,,	Amazon River, 1912	0·63	0·67	,,
,,	Buenos Aires, 1912	0·71	0·77	,,
Kohlrausch	Seeham (Salzburg), 1912–13	1·05	1·05	Direct.
Dobson	Eskdalmuir (Scotland), 1909–11	0·92	0·93	,,
Gockel	Eggishorn (Switzerland), 1916	Up to 1·4	Up to 1·3	Indirect.
Knoche	Cordilleras (Bolivia), 1909	3·3	1·9	,,
Wigand	Balloon, 3,000 m., 1914–20	6 to 8	4 to 6	,,
,,	Balloon, 4,000 m., 1914–20	9·2	5·8	,,
Berndt	Atlantic Ocean, 1914	1·13	0·97	,,
Bauer, Swann and others	Pacific Ocean, 1907–16	1·30	1·30	,,
,,	,, 1915–16	1·30	1·31	,,
,,	Sub-Antarctic Ocean, 1915–16	1·29	1·26	,,
,,	Mean of land observations at various stations	1·08	1·22	,,

thoroughly studied.   Laboratory experiments show a definite decrease in the mobility of the small negative ions with high relative humidity, while the mobility of the positive ions remains practically unchanged.   Results of observations in the open air are rather contradictory. Schweidler, at Seeham (Salzburg), and Gockel, at Freiburg (Switzerland), found decreases in k_+ and k_- of 1 to 25 per cent. for an increase of the relative humidity from 40 to 90 per cent.   Kohlrausch, at Mattsee (Salzburg), and Berndt, at Buenos Aires, found, on the other hand, a slight increase in both mobilities with increasing humidity. Evidently the influence of moisture is often complicated by other factors.   Particularly strongly marked is the influence of the " Föhn " wind on the average mobility in Alpine valleys.   According to B. Huber, the mobility has about double the normal value when this wind is prevailing.

Regular daily variations are also found in the average mobility (Mattsee, Buenos Aires, Eskdalmuir, Kew) which are chiefly due, as are the local variations, to change in the number of dust nuclei.   The generally established diminution of ionic mobility during solar eclipses must be caused by secondary meteorological influences during the period of totality.

§ 13. Measurement of the Mobility and Number of the Large Ions.

The presence of slow-moving ions in artificially ionised gases was established by Townsend, McClelland, Lenard, Becker and others.   The existence of such " large ions " in free air was first proved, as has already been mentioned, by P. Langevin,[1] who also determined their number and mobility.   For this purpose also, as in the case of the small ions, the method used is Zeleny's " method of perpendicular velocities " in a cylindrical condenser.   The theory

[1] *Compt. Rend.*, **140**, 232 (1905).

of the measurement has already been dealt with in the general consideration of such aspiration apparatus (see § 7).

If a stream of air is passed with constant velocity through a cylindrical condenser, and if the potential on the inner electrode is continuously raised, the number of ions deposited on this electrode, and therefore the rate of discharge of the electrometer connected to it, will increase in a linear way until all the ions of one particular mobility are deposited on the electrode (for the moment only a few mobility groups will be assumed). The curve showing the change of current strength (rate of discharge) with potential will, therefore, start from zero, rise steadily to a critical value $\overline{V}$, where it will show a sharp bend. After this it will become parallel with the axis representing potential. If, now, other kinds of ion with the same sign are present, there must be in this curve as many points of inflection as there are mobility groups. The horizontal portion will not be reached until the potential has become so high that the ions of the most slow-moving group are completely deposited.

If $\overline{V}$ represents the potential at which a point of inflection in the potential-current characteristic curve occurs, then the mobility of the ions corresponding to this point will be

$$k = \frac{\phi}{2\pi \,.\, l\overline{V}} \,.\, \log r_a/r_i$$

If there are m points of inflection, m different mobility groups must be present, and their mobilities, $k_1 \ldots k_m$, may be calculated from the corresponding critical potentials $V_1 \ldots V_m$. ϕ in the above formula is the volume of air passed through the aspirator in a second, l is the length of the inner electrode, r_a and r_i the radii of the outer tube and the axial inner electrode. For practical reasons, in order to be able to work with moderate potentials, the values of r_a and r_i are chosen

close together, so that the air has only a very narrow space between the inner electrode and the outer tube in which to flow. In Langevin's apparatus the dimensions were $r_a = 3 \cdot 5$ cm., $r_i = 2 \cdot 5$ cm., $l = 120$ cm. A potential of 350 volts is then sufficient to precipitate all the slow-moving ions when the air velocity corresponds to a flow of 100 litres in six minutes.

The same apparatus can be used for the determination of the number of large ions, if the number of small ions is at the same time measured with an Ebert ion-counter or a similarly constructed aspiration apparatus. The same arrangement has also been used by P. Langevin and Moulin [1] for the continuous registration of the number of the small and large ions. Unfortunately, the apparatus is somewhat complicated, and it has, therefore, not been used by other authors. If the numbers of large and small ions per cubic centimetre are N and n respectively, the large Langevin aspirator gives the number (N + n), and the small one n, so that the number of large ions is obtained as the difference of the two measurements. A simpler form of Langevin's apparatus, which is, however, not suitable for registration, has been described by A. Gockel. [2] In this a single aspirator of about the same size as that of Langevin is used ; the inner electrode is connected to a quadrant electrometer, the rate of discharge of which is observed with gradually increasing field strength. The mobility and number of the various groups of ions is then calculated from the inflections in the current-potential characteristic so obtained, as in the original arrangement of Langevin. Similar apparatus was also used by A. Pollock [3] in the discovery of the " intermediate " ions, and by J. A. McClelland and H. Kennedy. [4]

[1] *Compt. Rend.*, **140**, 305 (1905) ; *Le Radium*, **4**, 218 (1907).
[2] *Neue Denkschr. Schweiz. Naturf. Ges.*, **54**, 1 Abh. (1917).
[3] *Le Radium*, **6**, 129 (1909) ; *Phil. Mag.* (6), **29**, 514, 636 (191)
[4] *Proc. Roy. Irish Acad.*, A, **30**, 72 (1912) ; **32**, 1 (1913).

The inflections in the current-potential curve, to which reference has already been made several times, are more pronounced, as O. Blackwood [1] has shown in experiments with artificially ionised air, when the inner electrode consists of two cylinders, one behind the other and separated by a short air space, the first being earthed and the second connected to an electrometer. This arrangement is, however, only suitable for the determination of the various mobilities of the groups of ions occurring in air, and not for the measurement of the corresponding ion numbers.

The number and the individual charge of the large ions have been measured by a peculiar method by J. J. Nolan, B. K. Boylan, and G. P. de Sachy ; [2] all the large ions were precipitated from the aspirated air in a cylinder condenser in the usual manner and the total charge thus determined. The number of large ions was found by examining the air before and after its passage through the condenser by means of Aitken's nucleus counter.[3] The tests made before passing through the electric field give the number of charged and uncharged nuclei, while the tests afterwards correspond to uncharged nuclei only. In this way it was established that the heavy ions in free air carry almost exclusively a single charge, while with stronger artificial ionisation, as, for instance, in flame gases, ions with multiple charges are in the majority.

[1] *Phys. Rev.* (2), **16**, 85 (1920).

[2] *Proc. Roy. Irish Acad.*, A, **37**, 1–12 (1925).

[3] This apparatus consists of a cylindrical chamber, hermetically closed at the top and bottom with glass plates, into which a small quantity of air can be drawn by means of a movable plunger. If the connecting cock is closed and the air in the chamber is subjected to a violent expansion by means of a sudden upward movement of the plunger, a cloud is formed, owing to the condensation of the water vapour (the chamber is artificially kept damp) on dust particles or other condensation nuclei of undetermined nature. The particles then sink to the bottom, where they collect on the glass plate, whose surface is micrometically divided so that they may be actually counted by means of a magnifying glass.

The large ions are formed by the attachment of small ions to the solid particles, such as products of combustion, dust particles, etc., or droplets of water, which are always floating in the air. In city air, which is always strongly contaminated with combustion products, there are always many more heavy ions than in pure country air. Large ions are also formed by other agencies. It has, for example, been established by P. Lenard and Ramsauer, and also by J. J. Nolan and J. Enright, that slow-moving ions are produced by irradiation with ultra-violet light. J. J. Thomson and P. Langevin have shown that water can exist in the atmosphere in the form of invisible droplets even before the saturation point is reached. The most probable value for the size of these drops agrees well with the dimensions of the large ions, as calculated from their mobility in an electric field. B. Chauveau calculates a radius of 10^{-6} cm. for the large ions formed from such water droplets.

The nature of the "intermediate ions," whose mobility lies between that of the small ions (1 to 2 cm./sec. : volt./cm.) and that of the large ions (0·0003 cm./sec. : volt./cm.), is not yet known with certainty. They have a mobility of the order of 0·1 to 0·01 cm./sec. : volt/cm. Besides Sydney, where they were found by A. Pollock, they have also been detected in other places, so that it can hardly be doubted that they are actually of general occurrence, though they probably appear only under particular meteorological conditions. Pollock found that intermediate ions cannot exist when the vapour pressure is high, since under these conditions they are converted into slow-moving ions.

According to Pollock, the number of slow-moving ions per cubic centimetre in Sydney is about 2,000, of intermediate ions 200 to 1,000 ; the number of small ions, on the other hand, was abnormally low (about 40). In agreement with this, it is found that the total conductivity

of the air in Sydney is some ten times smaller than in normal pure air. In Washington, Swann has actually found as many as 60,000 large ions per cubic centimetre. According to Gockel there are in Freiburg (Switzerland), on the average, 600 to 700 small ions of both signs together with 1,700 to 1,800 positive and negative large ions. In Dublin the number of large ions per cubic centimetre varies, according to Nolan, between 3,000 and 60,000, while in a small village on the Irish coast the number of large ions hardly amounted to 1,000.

By multiplication of the ion number per cubic metre by the elementary charge the " ionic content " is obtained. The free space charge may be calculated by adding the ionic contents of the small and large ions for each sign and subtracting the sums thus obtained for the two signs one from the other. Thus in Freiburg the ionic contents of the large and intermediate ions were

$$E'_+ = 0.83, \qquad E'_- = 0.85 \text{ ESU/c.m.,}$$

while the contents of the small ions were

$$E_+ = 0.33, \qquad E_- = 0.30 \text{ ESU/c.m.}$$

The space charge due to the large ions is therefore -0.02 ESU/c.m., to the small ions $+0.03$ ESU/c.m. The total free charge is therefore $0.03 - 0.02 = +0.01$ ESU/c.m.

Naturally, the total ionic content, like that of the slow-moving ions, is subject to considerable variations. A remarkable parallelism has been noted by Nolan between the potential gradient and the number of heavy ions; this is very clearly seen both in the daily variation of the two quantities and in the daily mean during a month. This behaviour is in very good agreement with the inverse relationship already noted between conductivity and potential gradient; with high values of the latter the number of small ions decreases, while that of the slow-moving ions increases considerably. Hence a diminution of conductivity is caused.

Few observations are available showing the dependence of the content of the large ions on meteorological factors, and the further investigation of the behaviour of these and the intermediate ions will certainly form a promising field for future research.

As a matter of fact, determinations of the free space charge of the air by the methods described above have only been carried out at a few stations. Usually in the neighbourhood of the earth's surface (*i.e.*, 1 to 2 metres above the ground) positive and negative space charges occur with equal frequency. This is seen, for instance, in the measurements of A. Gockel at Freiburg (Switzerland).

CHAPTER III

THE IONISERS OF THE ATMOSPHERE

§ 14. Summary of the Sources of Ionisation to be Considered. Ionising Agencies of Non-radioactive Origin.

THE extreme variability of atmospheric conductivity, ionic content, and other ionic constants with locality and time lead to the expectation that the observed ionisation phenomena of the air must be due, not to one, but to a multiplicity of ionising agencies. The problem then arises of examining all the sources of ionisation which can be active in the atmosphere, making quantitative tests of their activity, and finally deducing a kind of balance which shall show whether the known ionising agents are present in sufficient quantity to explain the experimentally observed conditions of ionisation, and, if possible, also their local and periodic variations.

It is convenient, for the consideration of the possible individual sources of ionisation, to divide them into two chief classes : those of radioactive and those of non-radioactive origin. Under ordinary circumstances the latter play a subordinate part on the surface of the earth. As will be shown later, the ionisation of our atmosphere is caused chiefly by the radiations of radioactive substances, the gaseous and solid decomposition products of radium (or uranium) and of thorium, together with a very penetrating radiation whose origin is not yet known with certainty. This so-called ultra-gamma radiation (*höhenstrahlung*) will be discussed at the end of this chapter (§ 23 (6)).

Before we turn to the consideration of the radioactive ionisers in the atmosphere a short description of the

ionisers of non-radioactive origin may be given here Such are :

1. The Photoelectric Effect (Hallwachs-Effect).—As is well known, this effect is shown by certain substances described as photoelectrically active, which possess the property of emitting electrons under the influence of light. At atmospheric pressure these electrons become converted almost instantaneously into normal small ions by agglomeration to molecules. In the neighbourhood of a photoelectrically-sensitive surface exposed to the action of light, negative ions are, therefore, formed exclusively. If an electric field is applied, a purely unipolar current is produced, since only carriers of the one sign are present. This process, as Elster and Geitel first pointed out, may be of considerable importance for the electrical balance of the earth's atmosphere, provided that sufficient photoelectrically sensitive surfaces capable of emitting electrons under the action of sunlight are present on the earth. Investigation of the most important constituents of the earth's surface (water, ice, stones, plants, etc.) has shown that, though some of them are photoelectrically sensitive to a small degree, the spectral regions which are active in exciting them to photoelectric emission (ultra-violet rays shorter than 200 $\mu\mu$) are completely absent in the lower layers of the atmosphere. It has, in fact, been established by balloon observations that even at a height of 9 km. the solar spectrum ends at $\lambda = 290 \, \mu\mu$. The great water surfaces of the earth, seas, rivers and lakes are, therefore, inactive, and so is the surface of the dry land. The somewhat greater photoelectric sensitivity of ice makes it possible, however, that in the highest cirrus clouds, which consist of ice needles, some photoelectric emission may be produced by the ultra-violet rays of the sun.

2. Ionisation by Ultra-violet Light.—The investigations of Lenard, J. J. Thomson, Branly and others have established the fact that, besides the effect mentioned

under (1), ultra-violet rays also bring about a strong ionisation in the volume of any gas through which they pass. This volume effect, also known as the Lenard effect, produces ions of both signs. In the chief constituents of the air (nitrogen and oxygen) the active rays are only those belonging to the shortest part of the ultra-violet region, from 120 to about 180 $\mu\mu$. Rays of longer wavelength than 180 $\mu\mu$ only act on certain impurities in the air, such as carbon dioxide and ammonia.

From what has been said under (1) it is, therefore, evident that within the troposphere no direct ionisation of the air can be caused by solar radiation. In very much higher layers of the atmosphere, however, and perhaps in those regions in which the phenomena of aurora borealis occur, an enormous ionisation may be produced during the day by the action of sunlight (*cf.* § 28).

W. F. G. Swann [1] has calculated that the conductivity produced in these regions is about 10^8 times greater than at the surface of the earth. It has been mentioned earlier that even in the first 10 km. of the atmosphere the conductivity has risen to ten times its value at the surface of the earth, and various authors have advanced the view that this is due to a downward diffusion of ions from the highly ionised layers of the stratosphere. To this it must be objected, however, that during this process—certainly a very slow one—the continuous recombination of positive and negative ions must very quickly diminish the number of remaining ions. Furthermore, ultra-violet light, besides acting as an ioniser, also forms cloud nuclei, *e.g.*, H_2O_2-particles in damp air, and solid particles from CS_2. Now this cloud-nucleus-forming effect of the ultra-violet regions of the solar spectrum reaches much farther down than the ionising effect, and therefore, even if the ions failed to recombine during their downward diffusion, they would, by deposition on cloud nuclei, rapidly lose their mobility.

[1] *Terr. Magn.*, **21**, 1 (1916).

It is, consequently, permissible to assume that no ions enter the troposphere by diffusion from higher layers.

3. Formation of Ions by the Spraying of Water (Lenard Effect) and Allied Phenomena.—Lenard showed in the year 1892 that during the spraying of water the newly-formed drops acquire a positive charge, while negative ions remain in the air. The phenomenon also takes place when single drops break up into smaller drops, when drops impinge upon a solid wall, or when a continuous stream of liquid is broken up. The same effect occurs during the passage of gas bubbles through liquids and during the breaking of bubbles on the surface of a liquid, etc. According to Lenard, the phenomenon may be explained by the assumption of electrical double layers whose thickness is of the order of magnitude of the sphere of attraction of molecular forces (10^{-6} cm.). Both charged layers lie within the liquid : in pure water the negative layer is outermost. The phenomenon described therefore occurs when particles are thrown out from this outer layer, or during changes in the surface. Naturally, the expulsion of the particles must occur so quickly that the natural tendency to recombination is overcome. Simple division of drops is not effective. If ions of one sign are formed exclusively or in excess, the phenomenon is spoken of as electrification ; if ions of both signs are produced, it is described as ionisation. From older investigations of Lenard, Kähler and Aselmann it appeared that only negative ions were formed in the surrounding air by the scattering of pure water. Recently W. Busse [1] has shown that by any kind of division, such as spraying, bubbling, and the falling of drops on an obstacle, positive ions also may be formed ; the amount is greatest during spraying. This is easily explained on the basis of Lenard's theory of double layer formation : after removal of the outermost negatively-charged layer, drops may be formed from the

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[1] *Ann. d. Phys.* (4), **76,** 493 (1925).

positive half of the double layer, now momentarily exposed on the surface ; these drops will naturally carry a positive charge.

It is directly obvious from their method of formation that ions produced by the Lenard effect belong to the class of slow-moving (large) ions. They carry single elementary charges (W. Busse, *loc. cit.*). Their mobility varies, as Busse has also shown, between fairly wide limits, and there is no particular mobility which is specially prevalent. In the case of water, small admixtures may influence the ion formation very decisively. If, for example, minute quantities of sodium chloride or sulphuric acid are added to the water, positive ions are produced in excess.

The importance of the Lenard effect as a source of ionisation in atmospheric layers near the earth cannot be regarded as very great. The effect occurs in waterfalls, rapids, in the sea on the broken tops of waves, and in surf. Accordingly, a high potential gradient is found in the neighbourhood of surf, pointing to the presence of an excess of positive ions in the air. During the scattering of fresh water, on the other hand, the space charge of the surrounding air is negative, as was found as early as 1786 in the neighbourhood of waterfalls by Tralles. On dry land, therefore, the Lenard effect can only come into play in a few special places ; the only permanent sources of an excess of large positive ions are the surf on coast lines and the broken wave tops. The magnitude of this effect cannot well be estimated with any accuracy. It cannot, however, play any very considerable part even over the sea, since the mean value of the potential gradient over the sea is even lower than over dry land. Therefore the Lenard effect can only contribute slightly to the conductivity of the air over the sea, since the ions produces by this effect are all of very small mobility.

Another problem is the share of the Lenard effect in

the production of electricity by rain and thunderstorms. G. C. Simpson has explained the electrical phenomena which occur during such storms by the use of this effect.

Seeing that alterations in the surface of liquids can be the cause of electrification and ionisation processes, it may be asked whether production of electricity can ever result from the mere evaporation of a liquid. Investigations of G. Schwalbe, H. Beggerow and A. Gallarotti have shown that no electrical charge can be produced in the vapour formed either from electrified or unelectrified liquids.

4. Other Sources of Ionisation of Non-Radioactive Origin.—Laboratory experiments have proved the existence of a series of such sources of ionisation : ion formation through chemical processes, by flames, by heated metals and metallic salts. These processes need not be considered in connection with atmospheric electricity. It must, however, be remembered that the continual emission of very finely-divided products of combustion in industrial regions has a very strong influence on several factors, such as ionic mobility, conductivity and potential gradient. Even at country stations abnormal results may be obtained through the whirling of dust or powdered snow in windy weather. Dust clouds usually have a strong negative space charge.

A further source of ions must be mentioned—ionisation by ionic collision. At atmospheric pressure this kind of ion formation does not occur till field strengths of more than 30,000 volts per centimetre are reached ; it therefore only comes into practical consideration in thunder clouds and lightning discharges. In such cases each single ion produces by collision enormous numbers of new ions whose path are dependent upon the direction of the greatest field strength ; in this way the propagation of the lightning flash is explained.

Finally, the ionising action of cosmic radiation must be

considered.   In the highest regions of our atmosphere, radiation reaching us from the sun may cause enormously high conductivity (*cf.* § 28).

§ 15. Radioactive Substances and their Radiations.

The radioactive substances which have been detected in traces in the earth's crust, in the sea, and in the air, play an important part in the ionisation of the atmosphere. In order to enable those readers who are not familiar with the principles of radioactivity to understand more easily what follows, a short account of the properties of these substances may be given here.

Certain elements, such as uranium and its products, radium and actinium, also thorium and others, have the property of emitting continuously invisible rays which ionise the air and other gases, cause certain substances to give off fluorescent light, and bring about chemical processes, acting, for example, on a photographic plate in a manner similar to light.

It has been found that the emission of these " Becquerel rays " is a phenomenon which accompanies atomic disintegration ; the atoms of the elements in question are not stable, but change into other kinds of atoms with the emission of rays.   Radium, thorium and actinium are converted in this manner into gaseous elements—radium emanation (radon), thorium emanation (thoron), and actinium emanation (actinon)—which belong chemically to the group of the inert gases argon, neon, etc., *i.e.*, they form no chemical compounds.   Further radioactive change of the three emanations gives rise to a number of successive, genetically-related radioactive substances, the so-called active deposits, which gradually collect on the walls of vessels containing emanation.   A portion of the active deposit also remains floating in the air, attached, for instance, to dust or cloud particles.   Since, on account of the method of their formation, the atoms of this deposit

are positively-charged, they may be collected on negatively-charged wires.

Each radioactive substance has a definite velocity of transformation characteristic of itself. The time in which the amount of a given substance has diminished to half its initial value by radioactive decomposition is known as the "half-value period." Its value is determined by continuous observation of the ionising power ("activity") of a given radioactive preparation, i.e., measurement of the saturation current. If the preparation consists of a single radioactive substance whose product is either inactive or else possesses so small an ionising power that it may be neglected, then the activity diminishes with time according to a simple exponential law,

$$I_t = I_o \cdot e^{-\lambda t},$$

where λ is the "disintegration constant" of the substance in question. This constant is inversely proportional to the period T, according to the equation

$$T = \frac{0\cdot693}{\lambda}$$

The value of the half-value period is very different for different radioactive substances. Thus for radium emanation it is 3·82 days, for thorium emanation 54·5 seconds, for actinium emanation 3·9 seconds. Thus, if a given quantity of radium emanation is taken, it will be transformed fairly quickly into the products radium A, radium B, radium C, etc., so that after 3·8 days only half the original amount will be left, after 7·6 days a quarter, and after 11·4 days an eighth. After a month, therefore, the amount still remaining is practically nil. The decomposition of thorium and actinium emanations takes place in a similar way, though more quickly. The direct conversion products of the emanations, and the emanations themselves, are of the greatest importance in connection with the ionisation of the atmosphere. The

short-lived emanations of actinium and thorium naturally cannot exist at great heights above the surface of the earth. All the radioactive substances in the atmosphere would soon vanish owing to decomposition were they not continuously regenerated from the earth's crust, which contains uranium and all its decomposition products down to radium itself, as well as the series of thorium and actinium products. A state is soon set up between the various decomposition products which is known as " radioactive equilibrium." In this state, in the average, each product of the series loses in unit time through decomposition just as many atoms as are formed from the foregoing member of the series (" parent substance ") in the same time.

Owing to the rapidity of the decomposition it is not possible to observe the presence of the short-lived substances, such as thorium emanation, radium A, and the like, by weighing or any visual measurements. Their existence is only shown by their ionising effect or other similar action.

Among the long-lived substances, which only decompose slowly, must be mentioned uranium and thorium, with periods of millions of years, and radium, with a half-value period of 1,580 years.

Radioactive substances emit three kinds of rays. (1) *The α-rays.* These are positively-charged particles (helium atoms) which are emitted from many radioactive substances during decomposition with velocities from 14,000 to 21,000 km. per second. In air at atmospheric pressure they have a range of action of 3 to 8·6 cm. Within this range they cause strong ionisation. An α-particle from radium C, for example, produces in the whole of its 7 cm. range about 200,000 pairs of ions. (2) *The β-rays.* These consist of electrons which are emitted by the decomposing atoms with velocities from 100,000 to nearly 300,000 km. per second. They are able

to penetrate layers of air of several metres thickness. The rapid β-particles are also capable of passing through metal plates 1 to 3 mm. in thickness. β-rays are similar in nature to cathode rays. (3) *The γ-rays.* These are light waves of extremely short wavelength, in some cases even shorter than the wavelength of Röntgen rays. Their wavelength lies in the region of 10^{-9} cm., *i.e.*, 0·1 Ångstrom units, and they are, therefore, more penetrating than Röntgen rays; for example, the γ-rays of radium C are reduced to half their initial strength by a plate of lead 14 mm. thick.

The table on p. 70 gives a summary of the decomposition products of radium, thorium and actinium, as far as they are of interest for the present work.

§ 16. The Radioactivity of Rocks and Water.

The first fundamental work on this question is due to J. Elster and H. Geitel. These two investigators found that the air in closed spaces, such as cellars and natural caves, caused rapid dissipation of electrical charges. By exposure of a wire charged to a negative potential of 2,000 volts for a number of hours in the Baumann Cave, in the Harz Mountains, they were able to show the presence of radium emanation and its decomposition products in the cave. The loss of activity of the wire accordingly followed the law of decay of the products of radium emanation. It was also shown that air drawn up from the ground contained radium emanation (Elster and Geitel, Ebert). After this a systematic examination was made of specimens of minerals from the most varied sources, and the conclusion was reached that all the solid constituents of the earth contain minute admixtures of radioactive substances. Such specimens, when finely powdered and placed on a metal pan in an ionisation chamber, all produce small but quite noticeable increases in the ionisation.

Uranium-Radium Series.

Element.	Half Value Period.	Radiation.
Radium (Ra)	1,580 years	α, β
Radium emanation	3·82 days	α
Radium A	3 mins.	α
Radium B	27 mins.	β, γ
Radium C (complex).	19·5 mins.	α, β, γ
Radium D	17 years	β
Radium E	4·9 days	β
Radium F (Polonium).	136 days	α
Radium G	(End product.)	

Thorium Series.

Element.	Half Value Period.	Radiation.
Thorium (Th)	1·5 . 10¹⁰ years	α
Thorium X	3·64 days	α
Thorium emanation.	54·5 secs.	α
Thorium A	0·14 secs.	α
Thorium B	10·6 hours	β, γ
Thorium C (complex).	60·8 mins.	α, β, γ
Thorium D	(End product.)	

Uranium-Actinium Series.

Element.	Half Value Period.	Radiation.
Actinium	—	—
Actinium X	—	—
Actinium emanation.	3·92 secs.	α
Actinium A	0·002 sec.	α
Actinium B	36 mins.	β
Actinium C	2 mins.	α
Actinium D	(End product.)	

The apparatus used by Elster and Geitel consists of a glass bell, of about 20 litres capacity, coated on the inside with wire netting ; this bell is cemented on to a metal plate, on which an Elster and Geitel leaf electroscope is fixed in such a manner as to be easily read from the outside. On the leaf carrier of the electroscope is fixed a conducting body consisting of a brass plate with three extension pieces (see Fig. 7). A metal cup containing about 125 grams of the finely-powdered specimen is placed on the brass plate. The loss of charge, proportional to the saturation current, is measured (in volts per hour,
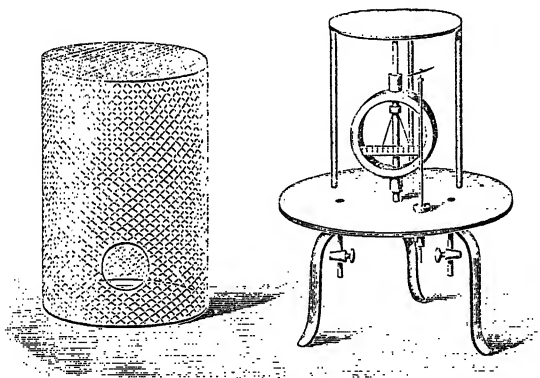

FIG. 7.—Bell apparatus of Elster and Geitel.

for example) before and after introduction of the powder. The increased loss of charge is a measure of the ionising power of the test powder. The arrangement may be considerably simplified by placing the powder to be tested on one of the plates of a large circular plate condenser which is connected with a sensitive electrometer, the other plate being connected to a source of constant potential of sufficient value to produce a saturation current. In this arrangement the rate of charge of the electrometer is proportional to the ionisation.

The ionisation currents observed with such arrangements, however, bear no simple relation to the radium or

thorium content of the samples under test. They arise chiefly from the α-radiation of the surface layers, and are therefore roughly proportional to the surface of the powdered sample. Part of the ionising action is also due to the β- and γ-rays from the deeper layers of the sample, and since these rays are absorbed to a different extent in different powders, comparison of the activity even of specimens of equal fineness in pans of the same size is rather unreliable. There is, in addition, the fact that most finely-powdered samples give off emanation gradually. Powders giving off much emanation will therefore give very high results in comparison with those in which the greater part of the emanation remains occluded in the individual particles of the powder. Consequently the method is used only for preliminary measurements, for which purpose it is very suitable, since it is very simple and necessitates no chemical treatment of the specimen.

For quantitative investigation of soil samples it must be borne in mind that almost all specimens contain radium and thorium, with all their products. By the " pan method " the simultaneous action of all these products is observed, but for quantitative purposes the examination for radium and thorium must be carried out separately.

We must limit ourselves to a short description of the principles of such measurements.

(a) **Quantitative Determination of the Radium Content.** —This is carried out by measuring the ionisation caused by the quantity of emanation produced by a weighed amount of the sample in a given time. According to the older methods worked out by B. Boltwood, H. Mache, St. Meyer, and E. v. Schweidler, as well as R. J. Strutt (now Lord Rayleigh) and others, a weighed, finely-powdered sample of the solid material to be examined is brought into solution by fusion with five to ten times its

weight of potassium and sodium carbonates. The solution is freed from emanation by boiling or bubbling air through it, and is then allowed to stand for some days (up to a month) in a wash bottle closed with stopcocks. At the end of this known period the emanation is pumped into an ionisation vessel, and the saturation current is measured and compared with that produced by known quantities of emanation. By applying the law of decay of radium emanation the equilibrium concentration, i.e., the amount of emanation which would be present in the sample after an infinite time, may be calculated from the known time of the accumulation in the solution. The radium content of the sample then follows directly from the equilibrium concentration.

Another method, described by J. Joly, later by Holthusen, and further improved by Ebler and by Fletcher, is the "fusion method." In this the finely-powdered, weighed mineral sample is directly melted with alkali carbonates and boric acid in an electric-arc furnace, the emanation set free during the fusion being led into a previously evacuated ionisation vessel.

(b) **Quantitative Determination of the Thorium Content.**—Thorium emanation is a radio element with such a rapid rate of decay (half-value period of 54·5 seconds) that it does not affect the above method for the determination of the radium content. For the determination of the thorium content of a mineral the sample is first brought into solution as described above, and the thorium content is then measured by the aspiration method of Joly. To carry out this process the solution is freed from radium emanation by bubbling; a stream of air of constant velocity is then led through it into an ionisation chamber connected in series with the solution. The ionisation chamber is in the form of a cylindrical condenser whose inner electrode is connected with an electrometer. A comparative test is carried out by passing a current of

air at the same velocity through a solution of known thorium content. A similar method could be applied for the determination of the actinium content of solutions of minerals, but the amounts of actinium and proto-actinium present in ordinary minerals are too small for quantitative measurement.

(c) **Results.**—The data obtained in examinations of the more important minerals and of samples of earth from all parts of the world are very numerous ; only a few of the more essential results can be mentioned here. Particularly noteworthy are the investigations of R. J. Strutt (now Lord Rayleigh), J. Joly, G. A. Blanc, E. H. Büchner, A. Holmes, H. Mache and Bamberger, and H. Hirschi.

The radium and thorium content of one and the same kind of mineral may vary very considerably from one sample to another. This is due to the fact that certain substances, often very rich in radium and thorium, which occur as admixtures in the mineral mass, are present in the form of unequally-distributed inclusions.

Volcanic rocks are on the average about twice as rich in radium and thorium as sedimentary rocks. The radium content of most minerals is of the order of 10^{-12} gm. of radium per gram, or a few millionths of a milligram per kilogram of mineral. Since from the age of the majority of minerals it may be assumed that the equilibrium between uranium and radium has been reached, and since $3\cdot4 \cdot 10^{-7}$ gm. of radium are present at equilibrium with every gram of uranium, it follows that the uranium content of the minerals may be taken as about $3 \cdot 10^6$ times the radium content.

The amount of thorium usually present is of the order order of 10^{-5} gm. of thorium per gram of mineral.

The small radium and thorium content of the sedimentary rocks is explained by the assumption that during their formation the radioactive constituents were partially dissolved out and carried away into the oceans.

The average amounts of radioactive substances in the minerals of the earth's crust (per gram) are estimated by Joly and Lord Rayleigh at $1.5 \cdot 10^{-12}$ gm. radium and $1.5 \cdot 10^{-5}$ gm. thorium. To arrive at the amounts per cubic centimetre of mineral the above figures must be multiplied by about 2.5. The discovery of the wide distribution of radioactive substances in the earth's crust is due to the extraordinary sensitiveness of the methods of measuring radioactivity. Actual separation of radioactive substances, such as radium and mesothorium, is only possible in the case of a few relatively rare minerals, such as pitchblende, carnotite, monazite, etc. Extraction of radium from ores containing less than 10^{-9} gm. of radium per gram of ore is not profitable. Owing to the great rarity of the ores mentioned, containing 100,000 times as much radium as ordinary minerals, their discussion is not necessary from the point of view of atmospheric electricity.

Many salts of uranium, radium and thorium are soluble in water, and it is therefore easily understood, in view of the wide distribution of these radioactive substances in the rocks and other constituents of the earth's crust, that the seas and lakes also contain traces of radioactive elements in solution.

The presence of uranium in sea water was demonstrated by Joly. Still easier is the identification and determination of radium in sea and fresh water. The method is the same as in the case of minerals. The water to be tested is evaporated and the residue redissolved; the emanation produced by this solution in a given time is then collected and measured.

The amount of emanation present in a freshly-taken sample of water may be either greater or smaller than the equilibrium amount corresponding to its radium content. In open waters the latter is the case, since the constant mixing of the water with air, due to waves, etc., con-

tinually removes emanation from the surface layers into the air. In springs, on the other hand, the amount of emanation is usually much greater than that corresponding to the equilibrium amount of the radium present in the sample ; spring water can, in fact, under some circumstances, absorb quite considerable quantities of radium emanation during its passage through the rocks without dissolving any actual radium.

The average radium content of sea water may be set at about $2 \cdot 10^{-15}$ gm. of radium per cubic centimetre, but the results of different observers vary very considerably with the locality in which the samples were taken. Samples drawn near the coast are somewhat richer in radium than those from the middle of the ocean. According to Joly, local precipitation of radium may be caused by micro-organisms occurring in sea water (sulphur bacteria) ; in this way he readily explains the enormously high radium content of the deep-sea sediments examined by him. In the Pacific and sub-Antarctic oceans, according to C. W. Hewlett, the radium content is less than $1 \cdot 10^{-15}$ gm. per cubic centimetre. In the Atlantic the smallest value is $0 \cdot 3 \cdot 10^{-15}$, the largest $40 \cdot 10^{-15}$. The latter measurement was made in the neighbourhood of the Irish coast. In the Adriatic Sea the content is $2 \cdot 10^{-15}$ gm./c.cm., according to H. Mache.

River-water samples from the St. Lawrence River, the Nile and the Cam (England) show radium contents of the same order of magnitude as sea-water samples. The thorium content of sea water is about 10^{-8} to 10^{-7} gm. thorium per cubic centimetre.

Spring waters almost always contain traces of radium emanation, and often appreciable quantities of dissolved radium as well; Mache, for example, found, in the neighbourhood of the hot springs of Bad Gastein, springs containing 10^{-13} gm. of radium, or about 100 times as much per cubic centimetre as sea water. The amount of

radium emanation is, however, in most cases of much more importance.

The unit quantity of radium emanation, as decided upon by the Brussels International Radium Congress (1910), is the " Curie " ; this is the amount of radium emanation which is in equilibrium with 1 gm. of radium. This unit, and even its millionth part, the microcurie, is still too large for the minute quantities occurring in spring water. For this purpose various other units are in use. In Germany and Austria the so-called " Mache unit " was used for a long time as a measure of the concentration of emanation in spring waters and gases. A spring water or gas is said to have an emanation concentration of x Mache units when the amount of emanation from 1 litre of the sample produces in an ionisation vessel a saturation current of x thousandths of an electrostatic unit, after allowing for the activity of the subsequent products of decay. One Mache unit corresponds to $3 \cdot 64 \cdot 10^{-10}$ curie/ litre.

Another unit, chiefly used by French investigators, is the milligram-second, or the amount of emanation produced by 1 mg. of radium in one second. An emanation content of 1 mg.-sec. per litre corresponds to $5 \cdot 76$ Mache units.

At a conference of radiologists in Freiberg (Saxony) in 1921 the adoption was recommended of another practical unit for measuring the emanation content of springs, the " Eman," corresponding to 10^{-10} curie per litre. On account of its simple relationship to the international unit, the curie, it is to be hoped that the use of this unit will become general. One eman corresponds to $0 \cdot 275$ Mache unit.

We have discussed fully the various units in use for giving the emanation content of spring waters and gases, because these units will be needed again in speaking of the emanation content of the free atmosphere and of the air occluded in the soil.

The emanation content of spring water and natural gases is of significance in connection with the ionisation of the atmosphere only at certain special places, such as the sources of springs of high activity. We cannot here go into the importance of the activity of springs in medicine and geology.

Special apparatus is in use (the so-called "Fontactometer") for the measurement of the activity, *i.e.*, the emanation content, of springs. The number of springs already examined is enormous.[1]

The strongest radioactive springs (Oberschlema and Brambach, in Saxony, and St. Joachimsthal, in Czechoslovakia) have an emanation content up to about 10,000 eman = 10^{-6} curie/litre. Even springs of 200 eman are considered strongly active. Ordinary springs on the Alps show activities of 0·5 to 10 eman.

The sedimentary deposits from springs—especially from hot springs—often contain quite considerable amounts of radium and thorium products. Examples of this are the "Fango" of Battaglia, the sediment from the famous hot springs of Gastein, known as Reissacherite, the sediment from Kreuznach, Nauheim, Echaillon, etc.

§ 17. The Radioactivity and Ionisation of the Soil Gases.

All the constituents of the earth's crust, and therefore all varieties of soils, contain radium and thorium and their disintegration products, and, on the other hand, it has been shown that all samples of earth give off emanation ; it is, therefore, quite understandable that the soil gases which are in intimate contact with the earth and fill all the rifts and crevices ("soil capillaries"), should contain radium and thorium emanation. This was first proved experimentally by J. Elster and H. Geitel,[2] who were the

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[1] See A. Gockel, "Die Radioaktivität von Boden und Quellen" (Vieweg, 1914). This work also contains a bibliography up to 1914.

[2] *Phys. Zeitschr.*, **3**, 574 (1902).

first to devise a practical method for determining the amount of radium emanation in the soil gases. This method is still in principle employed to-day. A bore-hole is made in the earth by means of a borer and a metal or glass tube is inserted to the required depth ; the tube is connected by a short piece of rubber tubing to an ionisation vessel provided with two stopcocks. The second cock leads to a water pump, a rubber bulb, or some similar arrangement, which allows a measured quantity of air to be drawn into the ionisation vessel. As soon as the ionisation vessel (for example, an Elster and Geitel bell apparatus) is filled with the soil gases, the rate of discharge per hour registered by the electroscope increases to several times its normal value. Within the next three hours after filling the apparatus the rate of discharge increases still further, corresponding to the subsequent formation of radium A, radium B, and radium C from the emanation present in the sample. Instead of filling the apparatus with soil gases on the spot, it is much more convenient to fill evacuated flasks with the samples, and afterwards to transfer their contents to the ionisation vessel by pumping or by forcing out with water. Thorium emanation and its products cannot interfere with Elster and Geitel's method, since they disappear by radioactive decay after a few minutes. If it is required to measure the quantity of thorium emanation, it is consequently necessary, as in the case of solutions of minerals, to apply an aspiration method (see below).

Measurements of the quantity of radium emanation in the soil gases have been made by the Elster and Geitel method, or by one similar in principle, by the following investigators : H. Ebert and P. Ewers [1] (Munich), H. A. Bumstead and L. P. Wheeler [2] (New Haven, U.S.A.),

[1] *Phys. Zeitschr.*, **4**, 162 (1903).
[2] *Amer. Journ. of Sc.* (4), **17**, 97 ; **19**, 16 (1904–5).

H. Brandes [1] (Kiel), von dem Borne [2] (Erzgebirge), R. Schenck [3] (Kiel), A. Gockel [4] (Freiburg, Switzerland), J. C. Sanderson [5] (New Haven, U.S.A.), J. Satterly [6] (Cambridge, England), J. Joly and L. B. Smyth [7] (Dublin), K. Kähler [8] (Potsdam), J. R. Wright and O. F. Smith [9] (Manila, Philippines), J. Munoz de Castillo [10] (Madrid), P. J. Olujic [11] (Freiburg, Switzerland). The results, as far as they can be calculated in curie/c.cm., are collected in the following table :—

Observer.	Nature of Soil and Depth of Borehole.	Radium Emanation Content (Curie/c.cm.).
Ebert-Ewers	Clay soil, 160 cm.	About $400 . 10^{-15}$
Gockel	"Moränen-Schotter"	73 to $270 . 10^{-15}$
Olujic	Clay soil, dry	$1,220 . 10^{-15}$
,,	,, wet	193 to $328 . 10^{-15}$
Satterly	,, 240 cm.	$250 . 10^{-15}$
Sanderson	Red sandstone, 120 cm.	$240 . 10^{-15}$
Joly and Smyth	,, ,, 20–150 cm.	$180 . 10^{-15}$
Kähler	Alluvial sand, 75 cm.	8 and $15 . 10^{-15}$
Wright and Smith	,, ,, 30 cm.	30 to $70 . 10^{-15}$
,, ,,	,, ,, 70 cm.	200 to $300 . 10^{-15}$
,, ,,	,, ,, 120 cm.	270 to $300 . 10^{-15}$

The mean value for the amount of radium emanation in the soil gases, as obtained from a majority of the observations, is therefore about $2 . 10^{-13}$ curies/c.cm. This is about 2,000 times as great as the average emanation content of the free atmosphere (cf. § 20), and about one-tenth of the amount which would be in equilibrium with

[1] *Dissert*, Kiel, 1905.
[2] *Habilit. Schrift*, Breslau, 1905.
[3] *Jahrb. f. Rad. u. Elekt.*, **2,** 19 (1905).
[4] *Phys. Zeitschr.*, **9,** 304 (1908).
[5] *Phys. Zeitschr.*, **13,** 142 (1912).
[6] *Proc. Camb. Phil. Soc.*, **16,** 360, 514 (1912).
[7] *Irish Acad. Proc.*, **13,** 148 (1911); *Phil. Mag.* (6), **24,** 632 (1912).
[8] *Veröff. Kgl. Preuss. Met. Inst. Potsdam*, No. 267 (1913).
[9] *Phys. Rev.* (2), **5,** 459 (1915).
[10] *Bolet. Inst. del Radioactividad*, Madrid, **5** (1913).
[11] *Jahrb. f. Rad. u. Elektr.*, **15,** 158 (1918).

the average amount of radium in the soil. Granite formations contain the largest amount of emanation and sandy soils the least. It is, however, not possible to draw any satisfactory conclusions as to the radium content of a particular kind of soil from the amount of emanation in the soil gases, since weathered rocks of relatively small activity often give up more emanation than non-disintegrated rocks of higher radium content.

The amount of emanation in the soil gases may vary very considerably in one and the same place ; the maximum and minimum values in many localities may stand in the relation of 1 : 4, or even 1 : 8.

Naturally the emanation content of the soil gases is determined not only by the amount of emanation given off by the particular soil, but also by the permeability of the soil. Heavy rains and surface freezing cause accumulation of emanation at greater depths. Warming of the soil, particularly by strong sunlight, also strong winds and fall of atmospheric pressure, increase the passage of emanation from the ground into the free air, and so diminish the quantity in the soil gases.

As will be seen from the table, the variations in the emanation content of the soil gases become smaller as the depth from which the sample is taken becomes greater. According to Wright and Smith, the emanation content of the soil gases appears to become constant at a depth of $1\frac{1}{2}$ to 2 metres. At such depths it is evident that the passage of emanation from the surface layers into the free air will cease to influence appreciably the emanation content of the soil gases.

The natural gases which emerge from the earth at many places also contain emanation. Von dem Borne (*loc. cit.*) has found 10^{-12} curie/c.cm. of emanation in the gas of mines, while Satterly obtained somewhat lower values in tests of marsh gas at Cambridge. The vapours emitted

by volcanoes are also active (*cf*. C. Bellia [1]). P. Ludewig and E. Lorenser [2] have also found considerable amounts of emanation in the air from deep bore-holes at Ober-schlema.

The presence of radium and thorium emanation in the soil gases may also be demonstrated indirectly by exposing a wire charged to a high negative potential for some hours (or up to as much as four days) in a bore-hole in the earth, or in a vessel filled with soil gases or with a steady stream passing through it (H. M. Dadourian,[3] A. Blanc [4]). As is well known, under these conditions the first solid decomposition products of the emanations (radium A, thorium A) are deposited on the wire ; by introducing the latter into an ionisation vessel the activity may then be measured. Conclusions as to the relative proportions of radium and thorium products may then be drawn from the rate at which the activity of the wire diminishes.

The only direct measurement up to the present of the amount of thorium emanation in the soil gases is that by J. C. Sanderson.[5] The method—an aspiration process—is very complicated, since the radium emanation has first to be removed, and, in addition, experiments have to be made with emanating thorium salts to determine the amount of thorium corresponding to a given ionisation.

Sanderson found that in clayey sandstone soils 1 c.cm. of soil gases contained a quantity of thorium emana-tion corresponding to an equilibrium concentration of $1 \cdot 08 \cdot 10^{-6}$ gm. of thorium. Since 1 c.cm. of soil contained about $0 \cdot 37$ c.cm. of air, the quantity of thorium emanation found per unit volume corresponded to about one-tenth of the amount which was actually present in the particular

[1] *Nuovo Cimento*, **13**, 525 (1907).

[2] *Zeitschr. f. Phys.*, **22**, 178 (1924).

[3] *Phys. Zeitschr.*, **6**, 98 (1905) ; *Amer. Journ. of Sc.* (4), **19**, 16 (1905).

[4] *Phil. Mag.* (6), **13**, 378 (1907) ; *Phys. Zeitschr.*, **9**, 294 (1908) ; *Jahrb. f. Rad. u. Elektr.*, **6**, 502 (1909).

[5] *Amer. Journ. of Sc.* (4), **32**, 169 (1911) ; *Phys. Zeitschr.*, **13**, 142 1912)

kind of stone in question ; the remainder was occluded in the solid.

According to Sanderson and Blanc, more than half of the total ionisation of the soil gases is due to the activity of thorium products.

As far as atmospheric ionisation is concerned, the amount of radium and thorium emanation contained in the soil gases is not of so much importance as the quantity which escapes into the free air. This exhalation of emanation by the earth may be measured by two methods, one of which is due to H. Ebert,[1] the other to J. Joly and L. B. Smyth.[2]

Ebert's method allows of the automatic and continuous registration of the amount of emanation emerging from the ground, without, however, distinguishing between the action of the radium and thorium emanation ; it is carried out as follows. A cylindrical hole about 1 metre deep and 45 cm. wide is made in the ground ; the sides of the hole are covered with a metal casing, while the bottom is left uncovered so as to allow of the escape of the emanations together with the other soil gases. In this hole is hung a cylindrical condenser, consisting of wire gauze and a central rod supported on insulating hooks. The outer electrode is connected to a battery, the inner to a recording electrometer. The top of the hole is covered with a metal lid which has only small holes for the supporting wires and the electrical leads. The ionisation, registered electrically as the saturation current in the hole, corresponds to the action of the radium and thorium emanation and their decomposition products present in the hole at the time. The activity of the decomposition products may be determined separately by removing the cylinder condenser from the hole from time to time and again measuring the saturation current.

[1] *Phys. Zeitschr.*, **10**, 346 (1909).

[2] *Phil. Mag.* (6), **24**, 632 (1912).

The apparatus described above was used for continuous records by L. Endrös [1] at Zusmarshausen (Bavaria) and Munich, and a somewhat modified form by K. Kähler [2] at Potsdam. The results of these experiments can only receive brief mention here. In such an apparatus, as Kähler remarked, the natural conditions under which emanation is exhaled from the earth are not exactly reproduced ; in this case the capillaries of the soil are replaced by a large space whose only connection with the outer air is through the holes in the metal cover, level with the earth's surface, through which the wires are led in. Expressing the activity of the emanation and its decomposition products in electrostatic units of current, the amount in the exhaled soil gases at Potsdam amounts to $0·22 . 10^{-7}$ per cubic centimetre, at Munich and Zusmarshausen to $1·2$ and $0·8 . 10^{-7}$ respectively. If, for the purposes of calculation, we assume that this current is due only to radium emanation and its decomposition products, the activity of the exhaled soil gases, expressed in curie/c.cm.[3] amounts to $3·6 . 10^{-15}$ (Potsdam), 13.10^{-15} (Zusmarshausen), and 20.10^{-15} (Munich). The ionising effect of the thorium emanation is here included with that of the radium emanation.

In order to judge the amount of emanation exhaled from the earth a direct determination is necessary. Ebert's method only gives the emanation content of the air which has already emerged, and not the amounts actually passing into the air per unit of time and surface (exhalation).

The method of Joly and Smyth, already mentioned,

[1] *Diss. München* (printed in Erlangen), 1909 ; ref. *Beibl.*, 1910, p. 1166.

[2] *Veröff. Preuss. Met. Inst. Potsdam*, No. 267 (1913) ; *Phys. Zeitschr.*, **15**, 27 (1914).

[3] One curie of radium emanation, with all its decomposition products up to radium C, develops a total saturation current of $6·1 . 10^{6}$ electrostatic units (see Meyer and Schweidler, " Radioaktivität," Teubner, 1916, p. 236.

allows of the direct measurement of the exhalation, at least as regards radium emanation. A cylindrical vessel (30 cm. high and 20 cm. wide) is set up directly on the ground and pressed in slightly. The upper end of the vessel (see Fig. 8) contains a suction tube of 1 cm. diameter, which ends at its lower part in a circular plate B, placed immediately above the surface of the ground. The suction tube leads through two drying vessels charged with sulphuric acid and calcium chloride to
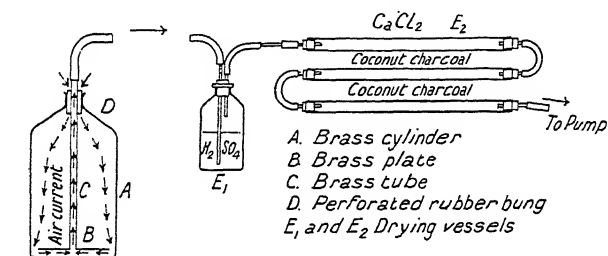

A. Brass cylinder
B. Brass plate
C. Brass tube
D. Perforated rubber bung
E_1 and E_2 Drying vessels

FIG. 8.—Apparatus for determining the quantity of emanation emitted by the soil. (Joly and Smyth.)

two quartz tubes joined in series, each containing 70 gm. of coarse-grained coco-nut charcoal, and finally to a suction pump. When the latter is set in motion, air passes through small side openings in the rubber stopper (not visible in the figure) into the apparatus, where it is forced to pass round the edge of the circular plate over the surface of the ground before finally entering the vertical suction tube. The pump only draws from 20 to 30 litres of air per hour, so that there is no danger of air being drawn from the capillaries of the earth by the streaming of the air from the edge to the centre of the plate by suction.

The coco-nut charcoal absorbs the whole of the radium emanation in the air as it passes through. At the end of the experiment (about an hour) the quartz tubes are removed and heated to redness in the laboratory. The emanation is thus removed, and may be led in a stream

of air into a previously-evacuated ionisation vessel. The ionisation developed is then measured and compared with that produced by a known quantity of emanation (by a standard radium solution). Besides Joly and Smyth in Dublin, J. R. Wright and O. F. Smith [1] have also worked with this method in Manila.

According to the Dublin measurements, the average amount of radium emanation passing into the atmosphere per square centimetre per second is

$$0.74 \cdot 10^{-16} \text{ curie.}$$

Smaller values were observed in Manila. The exhalation is dependent upon meteorological factors, and varies in the ratio of approximately 1 to 5. It reaches its greatest values on windy days, and is at its lowest on ground which is frozen or saturated with water.

§ 18. The Solid Radioactive Decomposition Products in the Atmosphere.

A. *Qualitative Methods.*

The immediate decomposition products of the emanations (radium A, thorium A, actinium A) are, as numerous laboratory investigations show, positively charged, and behave in an electric field as positive ions. J. Elster and H. Geitel [2] based on this fact a method for detecting the decomposition products of the emanations, and therefore, indirectly, the emanations themselves, in the free atmosphere (Elster and Geitel's wire method):

A wire 10 to 30 metres long and 0.5 mm. thick, charged to a potential of $-2,000$ to $-2,500$ volts, is stretched horizontally by means of specially-constructed insulating hooks at a height of several metres above the ground, where it is allowed to remain exposed for some hours.

[1] *Phys. Rev.* (2), **5**, 459 (1915).
[2] *Phys. Zeitschr.*, **2**, 590 (1901); **3**, 305 (1902); **4**, 96, 522 (1903).

By the action of the electric field all the positively-charged decomposition products in the neighbourhood are attracted to the wire. The active deposits so formed may be easily removed from the wire by rubbing with leather, and examined in an ionisation chamber. Usually, however, the wire is wound, after exposure, on to a frame and brought directly into an ionisation vessel; the ionisation produced is then used as a measure of the " activity " of the air. Elster and Geitel call the " activity of the air " unity when, after exposure for two hours, each metre of the wire causes a voltage loss of 1 volt per hour in an ionisation chamber whose electrical capacity (with the electroscope) is 14 cm. The voltage loss per hour caused by 1 metre of the wire is called the " activation number " (A).

Elster and Geitel's wire method affords a very simple and easily-handled apparatus for measurements in the field, and numerous observers have carried out measurements of the activation number A in the most varied localities. In the Alps, the values of A so obtained vary between 30 and 200, with an average value from 80 to 130. On the sea coast and over the sea the figures are about ten times smaller.

To-day the Elster and Geitel wire method is only used for preliminary measurements, since it was soon found that the fundamental assumption of Elster and Geitel— that the activity does not rise on increasing the voltage above 2,000—is not correct. H. Gerdien,[1] who has also measured the mobility of the charged radium A carriers in the atmosphere, noticed that, although these particles always behave as ions, in free space the number deposited increases continuously with rise of potential. The activation number is therefore determined not only by the number present, but also by their mobility in the electric field. The activation number must also depend

[1] *Phys. Zeitschr.*, **6,** 465 (1905).

upon the time of exposure, the strength of the earth's field, and the direction and strength of the wind.

The physical significance of the Elster and Geitel activation number is still further complicated by the fact that the decomposition products of radium emanation are not alone deposited. The activity of the wire as measured immediately after bringing it in falls rapidly in the first hour ; comparison of the form of the decay curves obtained after several hours with the curves calculated by H. W. Schmidt [1] for various exposure times for radium A, radium B and radium C leads to the conclusion that, for short exposures, only radium A is primarily deposited. With longer times of exposure the wires still show a residual activity even several hours after the end of the exposure, at a time, therefore, when the activity of the radium products has completely disappeared. The residual activity further diminishes with a half-value period of about eleven hours. The first observers of this residual activity, H. A. Bumstead,[2] J. E. Burbank,[3] G. A. Blanc,[4] A. Gockel,[5] and H. M. Dadourian,[6] quite rightly ascribed it to the deposition of thorium A and the subsequent formation from it of thorium B on the wire.

The fraction of the activity due to thorium rises with increased time of exposure. The maximum amount is not reached until three or four days' exposure, corresponding to the relatively long half-value period of thorium B. According to K. Kurz,[7] the relative activities of the radium and thorium fractions may be extrapolated from known times of exposure to infinite exposure (equilibrium). By analysis of the decay curves of the activity of the wire

[1] *Ann. d. Phys.* (4), **21**, 609 (1906).
[2] *Phys. Zeitschr.*, **5**, 540 ; *Amer. Journ. of Sc.* (4), **18**, 1 (1904).
[3] *Phys. Zeitschr.*, **6**, 437 (1905).
[4] *Phil. Mag.* (6), **13**, 378 (1907).
[5] *Phys. Zeitschr.*, **8**, 701 (1907).
[6] *Phys. Zeitschr.*, **9**, 333 (1908).
[7] *Habilit.-Schr.*, Munich, 1909 ; *Münch. Akad. Ber.*, **25**, 1.

J. Jaufmann,[1] A. Gockel,[2] K. Kurz (*loc. cit.*), and others succeeded in proving the presence of decomposition products of actinium emanation in the air. The amount of the actinium products is, however, very small (only 3 per cent. of the total activity, according to K. Kurz), and is for practical purposes negligible.

The percentage of thorium activity in the total activity falls with increasing potential of the wire, as remarked by Kurz (*loc. cit.*) and F. A. Harvey.[3] It also depends upon the height above the surface of the earth at which the wire is fixed. This was demonstrated experimentally by S. Kinoshita, S. Nishikawa, and S. Ono [4] : a vertical difference of 5 metres in height causes a diminution of one-half in the thorium percentage. Application of the theory of mass-exchange [5] in the atmosphere by irregular air currents to the distribution of the short-lived thorium emanation shows that the concentration of thorium emanation and of the still more short-lived thorium A has already sunk to about half the surface value at a few metres above the ground.

The contribution of the thorium activity to the total ionisation of the lowest layers of air can only be calculated indirectly, and with some uncertainty, from activation experiments by the wire method. Such calculations have been made by W. Wilson,[6] by Kinoshita, Nishikawa and Ono (*loc. cit.*), and by S. Sâto, from measurements made in Manchester and in Japan respectively. They yield the result that even in the immediate neighbourhood of the ground the radium emanation is responsible for one and a half to five times as much ionisation as the thorium emanation.

[1] *Meteorol. Zeitschr.*, **24**, 237 (1907).
[2] *Phys. Zeitschr.*, **8**, 701 (1907).
[3] *Phys. Zeitschr.*, **10**, 46 (1909).
[4] *Phil. Mag.* (6), **22**, 821 (1911).
[5] V. F. Hess and Wilh. Schmidt, *Phys. Zeitschr.*, **19**, 109 (1918).
[6] *Phil. Mag.* (6), **17**, 321 (1909).

Somewhat more certain results should be obtained by the effusion method of Sella.[1] In this all the active carriers, without regard to their mobility, are deposited on a metal plate by the electrical wind created by a strong electric field between this plate and a metallic point connected to an influence machine. Experiments of this nature have been carried out in Rome by G. A. Blanc [2]; according to these measurements the contribution of the thorium activity to the total ionisation is only from 10 to 20 per cent.

In general, in spite of the scarcity of observations, it may be concluded that thorium emanation and its decomposition products, even over dry land, contribute less to the total ionisation than radium emanation and its products.

Many attempts have been made to deduce the concentration of radium emanation in the atmosphere from measurements of the activation number ; in other words, to find a reduction factor connecting the two quantities (see K. Kurz, *loc. cit.*). On account of the many factors— all varying from time to time in different localities— which influence the activation of the wire, such calculations cannot be regarded, as W. F. G. Swann [3] has shown, even as rough approximations. The influence of wind velocity was first treated theoretically by Kinoshita (*loc. cit.*), and the figures obtained by him for the amount of emanation agree in the order of magnitude with the values obtained by the direct methods to be mentioned later. An exact theory of the collection of active deposits on charged wires was developed by W. F. G. Swann (*loc. cit.*). He takes account also of the fact that some of the active particles lose their charge by recombination with oppositely-charged ions, while a small number of the originally uncharged radium B and radium C carriers

[1] *Rend. Acad. Lincei*, **11** (1902).

[2] *Phil. Mag.* (6), **13**, 378 (1907) ; *Phys. Zeitschr.*, **9**, 294 (1908).

[3] *Terr. Magn.*, **19**, 23, 81, 171 (1914) ; **20**, 13 (1915).

obtain a positive or negative charge by attachment to small or large ions. Radioactive carriers are deposited together with the smoke and dust particles on horizontal wires exposed only to the action of the earth's field (Harvey, *loc. cit.*, S. J. M. Allen[1]). The fact that traces of radioactive decomposition products are deposited on uncharged or even on positively-charged wires was noticed by E. Sarasin and J. Tommasina,[2] and also by R. Schenck.[3]

B. *Quantitative Methods.*

When the unsuitability of the wire activation method was realised, methods were soon developed to allow of the complete precipitation of the radium and thorium decomposition products from a definite quantity of air. Here, again, two cases must be distinguished : (*a*) precipitation from air in motion (Gerdien's aspiration method), and (*b*) separation from a quantity of air at rest (process of A. S. Eve).

(*a*) **Gerdien's Aspiration Method.**—Gerdien [4] used a cylinder condenser exactly like the apparatus for the measurement of absolute conductivity, through which air was drawn in a steady stream of known velocity. If the electric field is sufficiently strong, all the positively-charged radioactive products in the air drawn through are deposited on the inner negatively-charged electrode. At the end of the period of aspiration the activated inner electrode is withdrawn and subjected to electrometric examination in an ionisation vessel, either all at once or in portions. With short times of aspiration—say, twenty to thirty minutes—almost all the activity on the electrode is due to radium products. For the study of thorium products aspiration times of at least several hours must

[1] *Phys. Rev.* (2), **7,** 133 (1916).

[2] *Arch. de Genève*, **18,** 620 (1904) ; *Phys. Zeitschr.*, **6,** 709 (1905).

[3] *Jahrb. f. Rad. u. Elektr.*, **2,** 19 (1905).

[4] *Abh. d. Kgl. Ges. d. Wiss. Göttingen* (N.F.), math. phys., Kl. V., Nr. 5, 1907 ; *Phys. Zeitschr.*, **6,** 465 (1905).

be chosen. According to Gerdien, it is also possible to calculate the mobility of the active particles from the distribution of the activity on the various parts of the inner electrode. The mobilities actually found for the radium and thorium products were from 0·00002 upwards to 25 cm./sec. : volt/cm. ; the range is thus much greater than that of the various kinds of ions in atmospheric air.

(*b*) **Eve's Method.**—A. S. Eve [1] used a large cylindrical iron vessel of 16 cubic metres volume, which was filled with ordinary air containing emanation. The active carriers were deposited quantitatively after an exposure of two hours on a wire stretched axially within the vessel and charged to − 10,000 volts. The activated wire was then examined electrometrically, and the amount of emanation corresponding to the observed activity was afterwards determined by a parallel experiment with known amounts of emanation in the vessel. An experiment of this kind in Montreal gave a figure of 10^{-16} curie/ c.cm. for the emanation content of the free air there, and about three times that value for the air of the laboratory. These results are in good agreement with the direct determinations, which will be discussed later.

The theory of the precipitation of active deposits from still air containing emanation has been worked out for the case of a cylinder condenser by Madame M. Curie ("Traité de Radioactivité," II., p. 474, Paris, 1910), and for the plate condenser by St. Meyer and E. Schweidler ("Radioaktivität," Leipzig, 1916, p. 463, second edition, 1927, p. 581).

We will now proceed to a discussion of the theoretical principles of the Gerdien aspiration method.

It has been shown by H. W. Schmidt and K. Kurz (*loc. cit.*) that when a negatively-charged conductor is exposed in a mixture of radium emanation, thorium emanation and actinium emanation, the primary products

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[1] *Phil. Mag.* (6), **10,** 98 (1905).

of decay, radium A, thorium A and actinium A, are chiefly deposited. It is therefore allowable, in order to simplify the deductions, to assume, as usual, that these A products are alone deposited under the influence of the field.

First, assuming that radium emanation alone is present, let us endeavour to calculate the radium A concentration of the atmosphere from the amount of activity collected on the axial electrode. If W (c.cm./sec.) is the air passed through the aspirator per second, and m the number of positively-charged radium A atoms primarily deposited per second, and if the field strength is so chosen that all radium A carriers, even those of small mobility, are deposited, then the number of radium A carriers in the free air per cubic centimetre is

$$v = \frac{m}{W.}$$

It is usual to give, not this number of radium A atoms, but the value of the saturation current which they can produce when the complete range of their α-particles is utilised ; this is equal to the product of the number of atoms, $\lambda_1 . v$, of radium A decomposing per second (decay constant λ_1) and the saturation current, k_1, produced by a single α-particle in the whole of its range. This constant k_1 is itself equal to the product of the number of pairs of ions produced by an α-particle and the elementary charge e.

The radium A content $\bar{s}$, expressed in electrostatic units, is accordingly

$$\bar{s} = k_1 . \lambda_1 . v = k_1 . \lambda_1 . \frac{m}{W} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Let λ_2 and λ_3 be the decay constants of radium B and radium C (the latter may be regarded as a single substance for the sake of simplicity, without affecting the accuracy of the calculation), and let the end of the period of aspiration be arbitrarily taken as the time $t = 0$. Then, if the duration of the aspiration is θ, the numbers of atoms of radium A, radium B and radium C on the axial electrode

at the end $(t = 0)$ will be given by the following expressions : [1]

$$A_\circ = \frac{m}{\lambda_1} \cdot (1 - e^{-\lambda_1 \theta}) \quad \cdots \cdots \quad (2)$$

$$B_\circ = \frac{m}{\lambda_2} \left[\frac{\lambda_2}{\lambda_2 - \lambda_1} (1 - e^{-\lambda_1 \theta}) + \frac{\lambda_1}{\lambda_1 - \lambda_2} (1 - e^{-\lambda_2 \theta}) \right] \quad (3)$$

$$C_\circ = \frac{m}{\lambda_3} \left[a(1 - e^{-\lambda_1 \theta}) + b(1 - e^{-\lambda_2 \theta}) + c(1 - e^{-\lambda_3 \theta}) \right] \quad (4)$$

where the coefficients a, b, c have the following significance :

$$a = \frac{\lambda_2 \lambda_3}{(\lambda_1 - \lambda_2)(\lambda_1 - \lambda_3)}, \quad b = \frac{-\lambda_1 \lambda_3}{(\lambda_1 - \lambda_2)(\lambda_2 - \lambda_3)},$$
$$c = \frac{\lambda_1 \lambda_2}{(\lambda_1 - \lambda_3)(\lambda_2 - \lambda_3)}.$$

The saturation current produced at the end of the exposure $(t = 0)$ by the decomposing atoms of the three substances is

$$I_\circ = \tfrac{1}{2} (\lambda_1 A_\circ k_1 + \lambda_2 B_\circ k_2 + \lambda_3 C_\circ k_3), \quad \cdots \cdots \quad (5)$$

where k_2 and k_3 are the saturation currents corresponding to a single a-particle of radium B and radium C respectively. Since radium B emits no a-particles and only a very slight β-radiation, the middle term in (5) may be practically neglected. The factor $\tfrac{1}{2}$ is due to the fact that when a radioactive product is deposited on a metal plate, half of the a-particles (those emitted towards the interior of the metal) are absorbed by the latter, and therefore cause no ionisation.

The strength of the saturation current at time $t = 0$ cannot be directly observed, since some time must always elapse before the electrode can be brought into the ionisation vessel and measured. The values observed later (up to fifteen minutes) can, however, be extrapolated back to $t = 0$ without difficulty.

[1] E. Rutherford, " Radioactivity," Cambridge, 1905 ; see also H. W. Schmidt., *loc. cit.*

Neglecting the middle term of (5) and substituting the values given by (2) and (4), we obtain

$$m = \frac{2I_o}{k_1(1 - e^{-\lambda_1\theta}) + k_3[a(1 - e^{-\lambda_1\theta}) + b(1 - e^{-\lambda_2\theta}) + c(1 - e^{-\lambda_3\theta})]}. \quad (6)$$

If C is the capacity of the electrometer with the ionisation chamber, and $\dfrac{dV}{dt}$ the rate of fall of potential at the electrometer in electrostatic units extrapolated to $t = 0$, then, applying equation (1),

$$W.\bar{s} = \frac{2\lambda_1 . C . \dfrac{dV}{dt}}{(1 - e^{-\lambda_1\theta}) + k_3/k_1[a(1 - e^{-\lambda_1\theta}) + b(1 - e^{-\lambda_2\theta}) + c(1 - e^{-\lambda_3\theta})]} (7)$$

The amount of radium A carriers in the free air, measured in terms of saturation current units, is therefore

$$\bar{s} = \frac{K}{W} . C . \frac{dV}{dt},$$

where

$$K = \frac{2\lambda_1}{(1 - e^{-\lambda_1\theta}) + k_3/k_1[a(1 - e^{-\lambda_1\theta}) + b(1 - e^{-\lambda_2\theta}) + c(1 - e^{-\lambda_3\theta})]}. \quad (8)$$

In order that these formulæ should hold, it is necessary that all the charged radium A carriers should actually be deposited. In order to ensure this it is only necessary to choose the difference of potential E in the condenser so high that the condition of Gerdien (see § 9),

$$E > \frac{G(r_a{}^2 - r_i{}^2) \log r_a/r_i}{2k . l},$$

is fulfilled. The mobility k of the active carriers in this formula may for practical purposes be taken at about 0·1 cm./sec.: volt/cm. (as a lower limit); according to Gerdien, more than 90 per cent. of the carriers behave as small ions.

Formula (8), of course, only holds strictly when no thorium products are deposited in appreciable amounts during the aspiration. With aspiration times of not more than sixty minutes this may be assumed to be the case.

In principle there are hardly any difficulties in the extension of the Gerdien aspiration method to the determination of the amount of thorium products in the atmosphere, all that is required being a longer time of aspiration.

Numerical values of the constant K in equation (8) have been calculated by K. W. F. Kohlrausch [1] for times of aspiration from two minutes up to 180 minutes.

The above-mentioned (p. 90) more exact theory of W. F. G. Swann on the precipitation of radioactive deposits is, of course, also applicable to the aspiration method (*i.e.*, the case of moving air). The simple theory given here will, however, be sufficient for practical application.

§ 19. Results of the Measurement of the Radium A Content of the Atmosphere by the Gerdien Aspiration Method.

Observations of the radium A content of the air have been carried out, by the methods described, by the following investigators : H. Gerdien,[2] Göttingen ; K. W. F. Kohlrausch,[3] Gleinstätten (Steiermark) and Seeham (Salzburg) ; K. Kurz,[4] Giessen ; V. F. Hess,[5] on the plains of the Danube near Vienna ; A. Gockel,[6] in the Adriatic and Ægean seas ; and E. Schrödinger,[7] Seeham.

Successive improvements were made by the authors mentioned, and the method was made more sensitive. P. H. Dike,[8] in Cambridge (England), instead of using a

[1] *Phys. Zeitschr.*, **13**, 1193 (1912).

[2] *Phys. Zeitschr.*, **6**, 465 (1905) ; *Abh. d. K. Ges. d. Wiss. Göttingen* (N.F.), V., Nr. 5 (1907).

[3] *Wien. Ber.*, **115**, 1263 (1906) ; **119**, 1578 (1910) ; *Phys. Zeitschr.*, **13**, 1193 (1912).

[4] *Dissert. Giessen*, 1907 ; *Phys. Zeitschr.*, **9**, 177 (1908).

[5] *Wien. Ber.*, **119**, 145, 507 (1910).

[6] *Phys. Zeitschr.*, **12**, 65 (1911).

[7] *Wien. Ber.*, **122**, 2023 (1913).

[8] *Terr. Magn.*, **11**, 125 (1906).

cylindrical condenser, allowed a strong stream of air to pass through a fine-meshed metal net charged to − 6,000 volts. After exposure the activated net was removed to an ionisation vessel, where its activity was measured. Unfortunately, it is impossible to make a subsequent recalculation of Dike's observations in absolute units.

Numerous measurements were carried out during the voyages of the experimental ship *Carnegie* (1915–21),[1] using a modification of Gerdien's method specially worked out by Swann for observations on board ship. A modification of Gerdien's method specially suitable for use in flying machines is due to H. Bongards,[2] who used it for a series of observations at heights of 3 to 4 kilometres.

1. Average Value of the Radium A Content near the Earth's Surface.—The mean values of the few available observations are collected in the following table. The earlier figures have been corrected by the application of the corrections of Hess and Kohlrausch (*loc. cit.*), later found to be necessary. The values of $\bar{s}$ give the radium A content of the air per cubic centimetre expressed by the saturation current in electrostatic units, assuming complete utilisation of the range of the α-rays.

Author.	Number of Experiments.	Mean Value of $\bar{s}$.
Gerdien, 1905 .	—	$12{\cdot}4 \cdot 10^{-11}$
Kohlrausch, 1906	37	$9{\cdot}3 \cdot 10^{-11}$
Kurz, 1907	9	$18{\cdot}4 \cdot 10^{-11}$
Hess, 1909	110	$3{\cdot}0 \cdot 10^{-11}$
Kohlrausch, 1910	31	$20{\cdot}2 \cdot 10^{-11}$
Schrödinger, 1913	105	$2{\cdot}7 \cdot 10^{-11}$
	Mean value .	$11{\cdot}0 \cdot 10^{-11}$ ESU/c.cm.

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[1] W. F. G. Swann, Publication No. 175, Vol. III., Carnegie Inst., Washington, p. 390. L. A. Bauer and Swann, *Carnegie Inst. Year-Book*, 1916, p. 326 ; 1917, p. 281. S. J. Mauchly, *Terr. Magn.*, **29**, 187 (1924).

[2] *Meteorol. Zeitschr.*, **36**, 339 (1919) ; *Phys. Zeitschr.*, **25**, 679 (1924).

All the measurements were made in the summer months. In the absence of further data, the mean value $11 \cdot 10^{-11}$ may be taken as fairly representative of the order of magnitude of the radium A content.

As regards the variations of the radium A content, it may be mentioned that Hess and Schrödinger have observed a regular daily change which was much more pronounced in Seeham than on the Danube plains. The increase in the radium A content with falling barometric pressure is also very noticeable ; in the Danube plains the radium A content is then twice as great as with rising pressure. Increase of temperature likewise has the effect of increasing $\bar{s}$, also high wind velocities and purity of the air (as measured by the visibility). All these influences are understandable when it is remembered that the radium emanation comes from the ground and must be driven out from the soil capillaries by fall of atmospheric pressure and intensive illumination of the surface by the sun, or by the suction of the wind.

The measurements of Bongards in flights at 3 to 4 km. show that at these heights the radium A content amounts at most to $0 \cdot 1$ to $0 \cdot 5 \cdot 10^{-11}$ ESU/c.cm., and is therefore 10 to 100 times smaller than near the ground. The considerable increase to $6 \cdot 7 \cdot 10^{-11}$ noted on two days may well be explained by a local rise of emanation due to some meteorological influence. Bongards (*loc. cit.*) is, on the other hand, of the opinion that emanation can at times reach the earth's atmosphere from the sun, an idea which can hardly be accepted, since it is contradicted by the measurements, mentioned in the next paragraph, of the emanation content at higher levels of the air.

2. Recalculation in Emanation Units.—A calculation of the emanation content from the data given is attended by considerable difficulties. The chief difficulty is that the above-mentioned determinations only give the quantity of positively-charged radium A carriers. Now

an appreciable fraction of the radium A originally present loses its charge by recombination with negative ions, and cannot therefore be deposited in the aspiration tube under the influence of the electric field. J. Salpeter [1] has calculated the relation between the number of these uncharged radium A carriers and the total number of the radium A carriers. According to this calculation the fraction which is charged amounts to

$$\eta = \frac{\lambda_1}{\lambda_1 + an,}$$

where λ_1 is the decay constant of radium A, and n the number of negative ions in the air per cubic centimetre. Taking the recombination coefficient a as $3 \cdot 10^{-6}$, and n as 700, corresponding to the average conditions in free air, η becomes $0 \cdot 64$, *i.e.*, under these conditions 64 per cent. of the radium A carriers are charged and 36 per cent. uncharged.

Owing to the uncertainty of the value of the recombination coefficient, Salpeter's correction cannot be expected to give more than the order of magnitude of the total amount of radium A and emanation in the air. More recent work has shown that in free air the value of a is considerably influenced by the ion number itself (see Chapter IV.), and if Schweidler's values for the recombination coefficient are used the conclusion is reached that only one-sixth of the radium A carriers remains charged.

Using the former figures for the calculation, it is found that an average of $11 \cdot 10^{-11}$ ESU/c.cm. for the concentration of positively-charged radium A carriers corresponds to an emanation content of

$$57 \cdot 10^{-18} \text{ curie/c.cm.}$$

On the assumption, however, that as much as five-sixths of the carriers are uncharged, the corresponding emanation content would be as much as $220 \cdot 10^{-18}$ curie/c.cm. As

[1] *Wien. Ber.*, **118**, 1163 (1909) and **119**, 107 (1910); *Bull. Acad. Cracovie*, A, 1910, p. 23.

will be seen in the next section, direct measurements give figures whose average value lies between the above limits.

J. Salpeter (*loc. cit.*) has also pointed out that some of the positively-charged radium A carriers escape measurement owing to the fact that they are deposited on the earth's surface under the influence of the normally downward-directed earth's field. Considering that the mobility of the carriers is no greater than that of the small ions, this correction cannot at the most raise the value of s by more than 5 per cent.

3. Observations over the Sea.—It is now of special interest to compare the land observations just discussed with those made over the sea. The first measurements of Gockel (*loc. cit.*, p. 96) on a voyage from Trieste to Constantinople had already shown that the quantity of radioactive decomposition products over the sea is appreciably smaller. But complete certainty was not attained before the very numerous observations carried out, with improved methods, on the voyages of the experimental ship *Carnegie* (see Bauer, Swann, Mauchly, *loc. cit.*, p. 97) on almost all seas. The following table [1] contains the results, taking into account the Salpeter correction for the uncharged radium A particles. The corresponding emanation content is calculated from the concentration of radium A.

The average of all the measurements made fairly close to land amounts to $7 \cdot 99 \cdot 10^{-18}$, while the mean of 299 values at very great distances from land is only $1 \cdot 14 \cdot 10^{-18}$ curie/c.cm. Since the emanation content over land is about $100 \cdot 10^{-18}$ curie/c.cm., it may be said that the value at points over the ocean at great distances from land is about 100 times smaller. These measurements afford the strongest proof that the radium emanation found in the

[1] The author owes this table to the kindness of Dr. L. A. Bauer, Director of the Department for Terrestrial Magnetism of the Carnegie Institute of Washington.

Place and Date.	Number of Measurements.	Mean Value in 10^{-18} Curie/c.cm.
Pacific Ocean, 1915. (Panama-Honolulu-Alaska-New Zealand.)	106	2·0
South Sea, 1915–16. (Circumnavigation, Lat. 44°–60° S.)	50	0·28
Pacific Ocean, 1916–17 . . .	46	4·04
Atlantic Ocean (near South American coast.)	7	29·9
Pacific Ocean, 1918 (280° E. Long. to Panama, from 56° S. Lat. to 3° N. Lat.).	15	0·79
Atlantic Ocean, 1918–20. (Crossing, then round the Cape of Good Hope into the Indian Ocean.)	94	3·06
Indian Ocean, 1920	31	1·45
Pacific Ocean, 1920–21 . . .	35	1·50

Average of 384 measurements, $2·65 . 10^{-18}$.

air originates solely on the solid parts of the earth. If, as Bongards suggested, atoms of emanation from the sun, driven by radioactive recoil, penetrated the earth's atmosphere, these invasions of emanation would have been detected during the six years in which the Carnegie Institution carried out observations, many of them in parts of the ocean far removed from land. This was, however, not the case.

Lastly, the connection between the amounts of emanation or its products in the air and the ionic content and conductivity is of great interest. Parallel observations of these factors have only been carried out by Hess (*loc. cit.*) and Schrödinger (*loc. cit.*). From these observations it is quite evident that increased concentration of radium emanation, radium A, and radium C corresponds to considerably increased figures for the ionic content or the ionising power ; it has been shown that the observed rise in the latter corresponds quantitatively to the increase in the emanation content (Hess). According to Schrödinger's measurements at Seeham, the daily

variation of conductivity is parallel with the change in the concentration of active particles, though the amplitude of the variation of conductivity at this place is four times as large as would be expected from the change in activity.   At this station, therefore, analogous variations in the concentration of thorium products and an inverse daily variation of the mobility of the active particles must be the cause of the great variations in conductivity.

§ 20. Direct Methods for the Determination of the Concentration of Radium Emanation in the Air, and the Results of these Determinations.

It has been shown that the methods previously described for indirectly determining the radium emanation content of the air from measurements of the concentration of radium A are attended with many weaknesses and uncertainties.   It is, therefore, evident that it is of great importance for investigations in atmospheric electricity to have methods which will render possible the direct determination of the emanation content.

Radium emanation, being one of the inert gases, can be separated from air containing it by absorption in liquids, adsorption on solid bodies, *e.g.*, powdered substances, and by liquefaction at low temperatures.   There are thus three possible classes of methods for its isolation. The detection and measurement of the amounts of emanation so obtained are performed by introducing it into an ionisation chamber and there comparing the ionisation developed with that produced by known amounts of emanation from standard radium solutions. A method for the determination of the emanation content, slightly differing in principle, is described under (4).   It must be remarked that all the direct methods given here are only applicable in the case of radium emanation. The separation of thorium and actinium emanations from

the air is impossible, owing to their rapid decomposition.

1. The Absorption Method.—Certain liquids, such as petroleum, oils, toluene, carbon bisulphide and others, have great absorptive powers for emanation at low temperatures. In the method worked out by H. Mache, with R. Hofmann[1] and T. Rimmer,[2] air of unknown emanation content is first passed for a long time through the absorbing liquid, kept cool in a freezing mixture, until equilibrium is reached. The vessel is then closed and raised to room temperature, and the absorbed emanation is driven over into an ionisation vessel by means of a rubber bellows. The method was used for the estimation of the emanation content of the air in a cellar and the relatively emanation-rich air of the laboratory. For free air it would be better to carry out the absorption, according to the process of J. Olujic,[3] at pressures of about 90 atmospheres, since otherwise the amounts of emanation separated would be too small.

2. The Adsorption Method.—The first useful method for the determination of the emanation content of free air was worked out by A. S. Eve,[4] after it had been shown by E. Rutherford[5] that freshly-heated coco-nut charcoal adsorbs emanation even at room temperature when the velocity at which the air is passed over it is not too great. The method was subsequently improved considerably by J. Satterly,[6] so that aspiration for three hours was sufficient to collect measurable quantities of emanation from the atmosphere. He employed the device of leading the air simultaneously through two systems of

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[1] *Phys. Zeitschr.*, **6,** 337 (1905).

[2] *Phys. Zeitschr.*, **7,** 617 (1906).

[3] *Dissert. Freiburg* (Switzerland), 1918 ; *Jahrb. f. Rad. u. Elektr.*, **15,** 158 (1918).

[4] *Phil. Mag.* (6), **14,** 724 (1907) ; **16,** 622 (1908).

[5] *Nature,* **74,** 634 (1906).

[6] *Phil. Mag.* (6), **20,** 1, 788 (1910).

tubes, one of which contained a radium solution of known concentration previously freed from emanation. The following scheme shows the arrangement :

$$CaCl_2 \text{ tubes—Porcelain tube—Manometer}$$
with charcoal

Free air—

Ra-—$CaCl_2$— Porcelain tube—Manometer
solution tube   with charcoal

—Pump
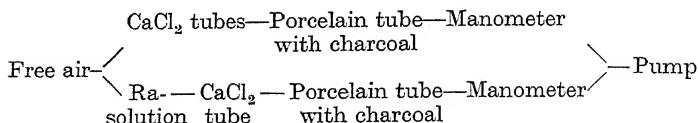
At the end of the time of aspiration (usually twenty-one hours) both porcelain tubes were removed, the emanation absorbed in them being driven out by heating to redness and led into a previously-evacuated ionisation vessel. In practice it was found necessary to work with high air velocities in order that the aspiration time might not be unnecessarily long, and only a certain percentage of the emanation was therefore absorbed ; this percentage had to be determined by special experiments. Further improvements in the method have been made by J. R. Wright and Smith,[1] also by Olujic.[2] It must be admitted, nevertheless, that the adsorption method is somewhat cumbersome and needs special control experiments to determine what fraction of the emanation in the air which flows over it is adsorbed in the charcoal. As regards the necessary standard solutions of known radium content, it must also be remembered that such solutions at times show a tendency to give off less emanation after a lapse of months or years, in consequence of the spontaneous precipitation of a part of the originally dissolved radium. It would be better to use solutions of uranium minerals of known radium content. Standardised solutions of this kind, which show particularly good constancy in their emanation output, are prepared and distributed for scientific purposes by the Physikalisch-Technische Reichsanstalt at Charlottenburg, near Berlin.

[1] *Phys. Rev.* (2), **5**, 459 (1915).
[2] *Loc. cit.*, p. 103.

3. The Condensation Method.—In 1903, H. Ebert [1] succeeded in separating the emanation from air containing it by cooling with liquid air ; he was thus able to give a direct proof of the presence of this radioactive gas. The process was worked out quantitatively by J. Satterly [2] and G. C. Ashman,[3] and later improved by J. Olujic [4] and A. Wigand.[5]

On account of the small concentration of radium emanation in the atmosphere (1 or 2 atoms per cubic centimetre), one can no longer speak of actual condensation, since the conceptions of the kinetic theory of gases, such as the vapour pressure, lose their significance under the circumstances. It is therefore necessary to regard the process as a kind of adsorption of atoms of emanation on the walls of the cooling apparatus ; this was very rightly emphasised by Wigand. The principle of the method may be very briefly described : fresh air is drawn by means of a pump through a system of tubes containing calcium chloride, sodium, sulphuric acid and caustic soda in order to absorb the water vapour and carbon dioxide. The rate of flow, measured manometrically or by a rotating gas meter, is fairly low ($0 \cdot 5$ to 3 litres per minute) and is kept constant during the experiment. The dried carbon-dioxide-free air is then passed into the cooler, consisting essentially of a system of narrow tubes in a hermetically sealed vessel maintained outside at a temperature below $- 150°$ C. by means of liquid air.

At the conclusion of the aspiration the cooling vessel is removed, taken out of the liquid air, and then connected with an evacuated ionisation chamber. As the cooler becomes gradually heated to room temperature the

[1] *München. Sitz.-Ber.*, **33**, 133 (1903).

[2] *Phil. Mag.* (6), **16**, 554 (1908).

[3] *Amer. Journ. of Sc.* (4), **26**, 119 (1908).

[4] *Jahrb. f. Rad. u. Elektr.*, **15**, 158 (1918).

[5] *Fortschr. d. Chem., Phys. u. phys. Chem.*, **18**, 5 Heft (1925) ; *Phys. Zeitschr.*, **25**, 684 (1924).

emanation is quantitatively driven into the ionisation vessel, the cooler being washed out with small quantities of fresh air. The measurement itself is made in the ordinary way by comparison of the ionisation with that of known quantities of emanation.

The time necessary for carrying out an experiment amounts to several hours, and the result is, therefore, always a mean value over that time. Olujic (*loc. cit.*) reduced the time of an experiment to one hour.

Still shorter times were used by Wigand (*loc. cit.*), who modified the method specially for use in flying machines. With so short a time of aspiration much greater air velocities must, of course, be used. Only a fraction of the emanation in the air will then be condensed, and this fraction must be determined by special experiments.

4. Deactivation Method.—Methods 1 to 3 depend on the concentration of the emanation from a large volume of air into a smaller volume, which is then introduced into an ionisation vessel. In places where the emanation content of the free air is relatively large it is also possible to apply the inverse process of removing completely the emanation from the air in a large ionisation vessel. The vessel, of about 20 litres capacity, is first filled with air, and the saturation current in the vessel is carefully measured. The air in the vessel is then completely freed from emanation by repeated passage over a strongly absorbing charcoal ("rademanit") and, after allowing time for the decay of the short-lived decomposition products radium A to radium C still remaining in the vessel, the saturation current is again measured.

Subtraction of this smaller value from that previously obtained, after the application of slight corrections and reduction to unit volume, gives the original quantity of emanation present in the vessel. The method was used by E. Schweidler at Seeham, and R. Zlatarovic [1] at

[1] *Wien. Ber.*, **129,** 59 (1920).

Innsbruck. In order to ensure accuracy and reliability in the result it is necessary that the residual ionisation in the vessel observed without emanation should be as constant and as small as possible.

5. Results.—All the results of direct measurements of the emanation content of the air near the earth's surface are collected in the accompanying table.

It will be noticed that the values in different localities vary widely. The highest value is found at Innsbruck, the lowest at Montreal. Omitting the observation on Mount Pauai (Philippines), the mean values shown in the table give a total average of about $130 \cdot 10^{-18}$ curie/c.cm. This value should correspond well with the average value over the earth's surface (over land).

Author.	Place and Time.	No of Expts.	Method.	Emanation Content in 10^{-18} Curie/c.cm.		
				Mean.	Max.	Min.
A. S. Eve . .	Montreal, 1907–8 . .	41	2	60	127	18
J. Satterly . .	Cambridge (England), 1908 .	8	2	88	—	—
,, . .	,, ,, 1908 .	21	3	124	—	—
,, . .	,, ,, 1909–10	58	2	105	350	35
C. C. Ashman .	Chicago, 1908 .	6	3	95	200	45
Wright and Smith	Manila, 1912–13 . .	21	2	82·5	154	42
,, ,,	,, 1913–14 . .	29	2	63·4	145	14
,, ,,	Mount Pauai (2,460 m.)	10	2	19·2	34	8
J. Olujic . .	Freiburg (Switzerland), 1917	36	2 and 3	131	305	54
E. Schweidler .	Seeham, Salzburg (Austria) .	46	4	77	315	—
	,, ,, ,,	61	4	125	406	—
R. Zlatarovic .	Innsbruck (Austria), 1919 .	49	4	433	1,110	40
A. Wigand . .	Halle (Saale), 1923–1924 (Germany) . .	—	3	—	500	300

Only observations by indirect methods are available over the sea (*cf.* § 19 (3)). The emanation content can vary very widely at one and the same place, as may be seen by considering the extreme values in the table.

Hardly any seasonal variation of the emanation content can be noticed at Montreal, Cambridge and Freiburg (Switzerland). In Montreal, however, low values have been registered at very low temperatures. In Manila the months with the highest wind velocity and the lowest rainfall (summer) show the smallest values. In the

temperate zones wind and rain are too evenly distributed to allow of such influences showing very clearly.

No regular daily variation has yet been detected, on account of the fact that each experiment lasts several hours. It is, however, remarkable that Wright and Smith in Manila, carrying out experiments over twelve-hour periods, from night to morning and from morning to night, found that the emanation content during the night was about twice as great as in the daytime. Closer investigation with periods of only six hours then showed that the emanation content is least during those periods in which the wind velocity reaches its maximum. The stagnant air during the night thus favours the retention of the emanation near the ground, while by day it is carried into higher layers by the general circulation of the air.

Apart from the influence of the wind, the emanation content is probably affected most strongly by the permeability of the soil. Rainfall, as all observers agree, lowers the emanation supply by closing the capillaries of the earth. Strong illumination of the ground by sunlight raises the concentration of emanation in the atmosphere by favouring the emergence of the soil gases richly charged with emanation.

The measurements of Wright and Smith at 2,460 metres on Mount Pauai, as well as five measurements in flight up to 4 km. by Wigand, show clearly that the emanation content of the atmosphere decreases very rapidly as the height increases ; but the measurements are at present not sufficiently numerous to enable the deduction of an empirical curve for the distribution. At higher altitudes the emanation content varies according to the origin of the air at the particular spot in question. In the presence of stable atmospheric layers (" protective layers ") the emanation content may often vary discontinuously. Beneath such protective layers the value is fairly high ; above them almost zero.

§ 21. The Equilibrium of Emanation in the Atmosphere.

Radium emanation and its products of decay are one of the chief sources of the ionisation of the air, and it is therefore necessary to see whether the experimentally-determined radium emanation content near the surface of the earth can be explained by consideration of the stationary condition of equilibrium brought about by the opposing factors which regulate the concentration of emanation, increasing it on the one hand by withdrawing emanation from the soil, decreasing it on the other by removal to higher layers in vertical air currents and by its continuous radioactive decomposition.

A theoretical investigation by V. F. Hess and Wilh. Schmidt,[1] based on the general theory of distribution in the atmosphere by irregular currents [2] developed by the latter author, supplies an answer to these questions, and, in addition, allows of the calculation of the distribution at various heights of radium emanation and all the other substances which occur in the atmosphere.

According to its rate of decay, the amount of each substance per unit volume decreases more or less rapidly with height. For radium emanation the distribution at various heights is as follows, the amount per cubic centimetre near the ground being set equal to 100 :

Height in Kilometres.	Emanation per c.cm.
0	100
1	49·4
2	25
3	13·5
4	7·4
5	2·5
8	0·9

The emanation content thus decreases by about half its value for every kilometre of height, according to an

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[1] *Phys. Zeitschr.*, **19**, 109 (1918).

[2] *Wien. Ber.*, **126**, 757 (1917) ; W. Schmidt, " Der Massenaustausch," etc. (Hamburg : Henri Grand, 1925).

exponential law. The figures in the table are, of course, only to be regarded as a rough approximation, since the distribution in the air varies very greatly. In any case, they should correspond well with the average values. Agreement with the results of direct measurements in flight can hardly be expected at the present time, since far too few measurements are available to give a true average.

On the basis of plausible assumptions as to the exchange by irregular currents in the lowest layers of the air, it follows in a similar way that the thorium emanation has practically disappeared at a height of 100 metres above the ground. The more long-lived decomposition products of thorium emanation can, however, persist at considerable heights. The concentration of thorium B should reach half its ground value at a height of 100 to 150 metres. The long-lived end products of the radium series, radium D to radium E, should be present in practically constant quantity up to a height of 10 km., provided that no separation by precipitation is to be expected.

The above-mentioned theory also permits of the calculation of the average amount of radium emanation emitted per square centimetre of the earth's surface (exhalation). The exhalation, calculated in this way, is from to 3 to $5 \cdot 10^{-17}$ curie/sq. cm. sec., in good agreement with experiment, which gives figures between 2 and $14 \cdot 10^{-17}$ curie/sq. cm. sec. (*cf.* § 17).

Taking into account newer data on the increase of the " coefficient of mass exchange " with the height, W. Schmidt[1] calculated that the radioactive substances diminish with the altitude much more rapidly than it is mentioned above and not according to an exponential law. According to W. Schmidt the concentration of radium emanation in 13 metres would be one-half of the concentration in 1 metre above the ground, and in 150 metres this concentration would fall to 1 per cent.

[1] Wilh. Schmidt, *Phys. Zeitschr.*, 27, 361 (1926).

The concentration of thorum emanation would fall to one-tenth in 160 cm. above the ground.

In view of the great difference between the emanation content of the soil gases and the free air, it is of great interest to see how much emanation passes into the free air by pure diffusion from the capillaries of the soil. This calculation was made by H. Mache.[1] A repetition of the calculation in the light of more modern data leads to the conclusion, contrary to that drawn by this author, that pure diffusion can at the most account for only one-tenth of the total measured exhalation. Pure diffusion cannot in any case suffice for the provision of the quantities of radium emanation required for the maintenance of the existing stationary state, and removal of emanation from the soil capillaries by irregular currents (wind suction, etc.), by the action of sunlight, and by fall of atmospheric pressure must greatly predominate.

Considerations as to the equilibrium of emanation in the atmosphere above the sea are also available,[2] but need partial revision in the light of the latest results of measurements by the Carnegie Expedition. In the middle of the ocean the emanation content of the air amounts to only about 1 per cent. of the average value over dry land, while near the coast, especially with a wind from shore, much larger values are found. It may therefore be regarded as certain that the quantities of radium emanation found over the sea originate chiefly from the dry land. Products of the thorium and actinium series do not occur far from land on account of their shortness of life. Radium emanation may be given off by sea water itself owing to the spraying of wave crests and by evaporation. The first factor cannot even be approximately estimated, while it may easily be shown that the quantities of radium emanation passing into the atmosphere by evaporation only amount to $\frac{1}{10000}$ of the exhalation of the dry land.

[1] *Wien. Ber.*, **114**, 1377 (1905).

[2] V. F. Hess, *Wien. Ber.*, **127**, 1297 (1918).

The equilibrium of emanation in the atmosphere over land and sea can, therefore, be fully understood, as has been shown, if the solid part of the earth's crust is regarded as the almost exclusive source of the emanation found in sea air.

A completely different view has been published by H. Bongards,[1] who advances the hypothesis that emanations and their decomposition products can reach our atmosphere from the sun. His measurements of the activation number by the Elster and Geitel wire method on high-flying kites at Lindenburg have shown a parallelism of the activation number at a height of 4 km. with the potential temperature of the layer of air in question and the solar activity. Highest values of the activation number coincide with the appearance of a group of calcium spots in the central meridian of the sun. Bongards also thinks that he can show a twenty-seven-day period in the activation numbers corresponding to the known period of rotation of the sun. He further lays stress on the parallelism between the variations in the activation numbers observed at Lindenburg and those of the emanation content measured at the same time (1913) by Wright and Smith in Manila. Finally, the occasional high emanation concentrations found by Bongards during his latest measurements in flight at 3 to 4 km. are explained by him on the assumption that from time to time radioactive substances due to solar activity enter into the earth's atmosphere.

A number of serious objections may be raised against the hypothesis of Bongards (A. Gockel [2]). A. Wigand is also opposed to the theory on the ground of the emanation measurements made by him in flight.

Above all, the measurements of the Carnegie Expedition

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[1] *Phys. Zeitschr.*, **21**, 140 (1920) ; **24**, 16, 295 (1923) ; and " Manuskript d. Vortrages der 88 Vers. Deutscher Naturf. und Arzte," Innsbruck, 1924, kindly communicated by the author (cf. *Phys. Zeitschr.*, **25**, 679 (1924)).

[2] *Phys. Zeitschr.*, **24**, 500 (1923).

at sea, mentioned above (§ 19 (3)), extraordinarily numerous as they are, and embracing a period of six years, would have given some indication of such invasions of emanation. It is a fact, however, that all the high values of emanation content observed during these voyages were obtained in proximity to the land or during winds blowing from land.

The fact that at heights of 3 and 4 km. amounts of emanation of the same order of magnitude as near the earth often occur is explained by Wigand as being due to the drawing of large masses of air from the earth's surface into these regions. Ordinarily rapid decrease of the concentration of emanation with height is the rule.

§ 22. Radioactivity of Atmospheric Precipitates.

C. T. R. Wilson [1] was the first to show that freshly-fallen snow or rain contains traces of radioactive substances. This may very easily be proved by evaporating about 100 gm. of rain water or melted snow soon after collection, and examining the residue in an ionisation vessel. The radioactive constituents may also be separated from rain water by precipitation with a few drops of barium chloride and sulphuric acid. The method worked out by A. Gockel and Th. Wulf [2] is particularly suitable.

The results of various investigators all show that the radioactive substances in precipitates consist essentially of the decomposition products of radium emanation (radium A, radium B, radium C). This may easily be shown by the decay curves. In some parts of the Central Alps and their neighbourhood traces of thorium products are also found. The precipitates falling on the sea in regions far from land are practically inactive, as the observations of P. Rouch [3] on Petermann's Island show.

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[1] *Proc. Camb. Phil. Soc.*, **11**, 428 (1902); **12, 17,** 85 (1903).
[2] *Phys. Zeitschr.*, **9**, 907 (1908).
[3] *Ann. Soc. Meteorol. France*, **59**, 117 (1911); **61**, 149 (1913).

This is easily understood when it is remembered that there the emanation content (of the air) is almost a hundred times smaller than over dry land.

According to observations by J. Jaufmann [1] on the Zugspitze, the activity of snow is many times greater than that of rain. The activity of snow can be of two kinds : freshly fallen snow, as also rain, hail and other forms of precipitate, contains only the decomposition products of the emanations. Snow lying on the ground can, on the other hand, contain also emanation itself, arising from the soil capillaries, as is shown by the much slower diminution of its activity. Dew is radioactive (Negro [2]), also hoar-frost (W. Budig [3]).

The precipitates evidently owe their radioactivity chiefly to absorption from the air through which they fall. It is therefore understandable that the snow-flakes bring relatively large amounts of active substances to earth, on account of their greater surface and longer path through the atmosphere. As M. Curie has shown that the radioactive carriers act as condensation nuclei, it is naturally quite possible that a portion of the precipitates which come to earth is " activated " directly in this way.

Systematic measurements of the activity of precipitates together with determinations of the emanation content of the free air, especially in stations at great heights, would most probably throw a very interesting light on the origin and cause of the formation of the precipitates in question (J. Reger,[4] A. Gockel [5]).

[1] *Diss. München. Techn. Hochschule,* 1908 ; *Meteorol. Zeitschr.,* **22,** 102 (1905) ; **24,** 337 (1907).

[2] *Phys. Zeitschr.,* **11,** 189 (1910) ; *Mem. Acad. Lincei,* **28** (1910) ; see also G. Costanzo and C. Negro, *Phys. Zeitschr.,* **7,** 350, 921 (1906), and *Jahrb. f. Rad. u. Elektr.,* **5,** 120 (1908).

[3] *Jahresber. Preuss. Meteorol. Inst., Potsdam,* 1911, p. 179.

[4] *Meteorol. Zeitschr.,* **39,** 144 (1922).

[5] *Meteorol. Zeitschr.,* **39,** 252 (1922).

§ 23. The Penetrating Radiation in the Atmosphere.

1. Historical Introduction and Summary.[1]—In the year 1901 Elster and Geitel,[2] as well as C. T. R. Wilson,[3] showed that completely enclosed air is always feebly ionised, even after the radioactive substances originally present have long since disappeared. McLennan and Burton,[4] as well as Rutherford and Cooke,[5] found that the ionisation in closed vessels may be considerably reduced by surrounding them on all sides with as thick a layer as possible of a material which is itself free from radioactive impurities. A part of the ionisation, therefore, arises from some cause outside the vessel, some radiation which, like the γ-rays of radioactive substances, possesses the power of penetrating metal walls of not too great thickness ("*penetrating radiation*").

Experiments by McLennan,[6] Wulf,[7] Gockel and Wulf,[8] Wright,[9] and others have shown that the ionisation is smaller when the ionisation vessel is set up over water or ice instead of over dry land. It was, therefore, concluded that the penetrating radiation was due for the most part to the radioactive substances present in the ground. The view was held by some authors that the radium emanation and its decomposition products in the air, together with the radioactive deposits (radium A, etc.) on the earth's surface carried down by the normal electric field in the atmosphere, also contributed very considerably

[1] For complete bibliography, see W. Kolhörster, "Die durchdringende Strahlung in der Atmosphäre" (Hamburg: Verlag Henri Grand, 1924).

[2] *Phys. Zeitschr.*, **2,** 116, 560, 590 (1900–1).

[3] *Proc. Camb. Phil. Soc.*, **11,** 62 (1900); *Proc. Roy. Soc.*, A, **68,** 151; **69,** 277 (1901).

[4] *Phys. Zeitschr.*, **4,** 553 (1902–3); *Phil. Mag.* (6), **6,** 343; *Phys. Rev.*, **16,** 184 (1903).

[5] *Phys. Rev.*, **16,** 183 (1903).

[6] *Phys. Zeitschr.*, **9,** 440 (1908).

[7] *Phys. Zeitschr.*, **10,** 997 (1909).

[8] *Phys. Zeitschr.*, **9,** 907 (1908).

[9] *Phil. Mag.* (6), **17,** 295 (1909).

to the total effect ; but this was contradicted by the results of experiment and calculation.

If the ground itself is the chief source of penetrating radiation, it is to be expected that this radiation will diminish rapidly as the height above the earth is increased. The earliest observations in towers actually did show a decrease, but a much smaller decrease than had been anticipated. The first balloon observations during an ascent by K. Bergwitz,[1] and on three ascents by A. Gockel,[2] were influenced by instrumental defects and yielded no quantitatively certain results. Gockel was, however, able to conclude that at heights up to 4,000 metres the total radiation is not appreciably different from that at the earth's surface. V. F. Hess [3] was the first to show, from ten balloon ascents with improved apparatus in the years 1911–12, that the penetrating radiation diminishes slightly up to 1,000 metres, but definitely increases again after 2,000 metres. From 3,000 metres upwards the increase becomes very great, and at heights of 5 km. the total ionisation in the vessel is already twice or three times as great as on the ground. *From these observations Hess concluded that there must exist a very penetrating radiation of extra-terrestrial origin which enters the atmosphere from above, and even at the earth's surface is responsible for part of the ionisation observed in the vessel.* W. Kolhörster [4] further improved the apparatus, and undertook five balloon ascents to still higher altitudes. Up to 5 km. the results of Hess were confirmed, and further rise to a height of 9 km. showed an enormous additional increase in the radiation. Later observations on mountains (Gockel, Kolhörster) also showed a definite increase in the radiation.

Although the existence of this new radiation has been

[1] *Habilit.-Schrift*, Brunswick, 1910.

[2] *Phys. Zeitschr.*, **11**, 280 (1910) ; **12**, 595 (1911).

[3] *Phys. Zeitschr.*, **12**, 998 (1911) ; **13**, 1084 (1912).

[4] *Phys. Zeitschr.*, **14** 1066, 1153 (1913).

called in question by some authors, the later measurements of its absorption coefficient by Kolhörster on the Jungfrau Ridge and on the Mönch (Switzerland), as well as the observations of R. A. Millikan and his collaborators, Otis, Bowen and Cameron, on mountains in California, in flying machines, and with pilot balloons and recording apparatus up to heights of 16 km., definitely prove the existence of this extraordinarily hard radiation coming from above.

Schweidler introduced the term " Hess-rays " for this radiation. We will use the term " ultra-gamma radiation " (introduced by Hess) or the German name. " *Höhenstrahlung* " [1] (first used by Kolhörster).

The ionisation observed in closed vessels is thus of very complex origin. In part it is due to radiation coming from outside and penetrating the vessel, in part also to radiation coming from the walls of the vessel itself, due either to traces of radioactive substances in the walls, or possibly also to a specific activity (not definitely proved) of the material of the walls. The radiation arising from the last two causes is called *residual radiation (wall radiation)*.

By careful choice and purification of the wall material it is possible to reduce the residual radiation to very small limits.

As a second source of the ionisation in the vessel there is the γ-radiation from the radioactive substances in the earth's crust (*earth radiation*) ; as a third, quantitatively not very important, source, the γ-radiation of the radioactive substances in the air (*atmospheric radiation*) ; and finally, as a fourth source of ionisation, the abovementioned *höhenstrahlung* (ultra-gamma radiation), whose

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[1] The more recent proof of the existence and great penetrating power of the *höhenstrahlung* by Millikan and his co-workers has led to the adoption by American scientific periodicals, such as *Science* and the *Scientific Monthly*, of the name " *Millikan rays* " for this radiation. Since it was only a question of the verification and development of the results of a discovery made by European investigators from 1911 to 1913, this nomenclature is both misleading and unjustified, and was accordingly not accepted in other countries.

penetrating power far exceeds that of the ordinary γ-rays (hence the term " ultra-gamma radiation ").

The cosmic ultra-gamma radiation also plays an important, if not decisive, part in the ionisation of the free atmosphere, since it is just as active over the ocean as over dry land, while, as we already know, all the other important ionising agencies are almost entirely absent over the sea. We will now discuss first the methods of measuring the ionisation in closed vessels, after which the results of observations of total radiation and of the four components will be considered. In conclusion, the origin of the ultra-gamma radiation will be treated theoretically.

2. Methods of Measurement.—The ionisation vessel is usually made of metal in the form of a sphere or cylinder. The inner electrode (an axial rod or a small ball in the centre of the vessel) is connected to a highly sensitive electrometer. The potential difference applied between the inner electrode and the wall of the vessel must be high enough to ensure saturation current ; with vessels from 1 to 4 litres in volume potentials of 100 to 200 volts are sufficient. Either a charging or discharging method may be employed. In the latter the electrometer and the inner electrode are charged to a sufficiently high potential, and the rate of discharge of the system is then continually observed. If C is the electrical capacity of the ionisation vessel with the electrometer, and if the potential is observed to fall from V_o to V_t volts in t seconds, then the loss of charge per second in electrostatic units is $C(V_o - V_t)/300\ t$, and this corresponds to the saturation current maintained by the penetrating radiation and the residual radiation in the vessel (volume W). If q is the required total ionisation (expressed in pairs of ions per cubic centimetre per second), and e the elementary quantum, it follows that

$$q = \frac{C}{300\ .\ e\ .\ W} \cdot \frac{dV}{dt},$$

where dV/dt is the loss of potential of the system in volts per second, which is identical with the actually observed value $(V_o - V^t)/t$ when the ionisation does not undergo quick changes. The insulation loss of the system is determined separately, and amounts at most to less than 1 per cent. of the observed total current. It is taken into account in the calculation of dV/dt by subtracting it from the observed current.
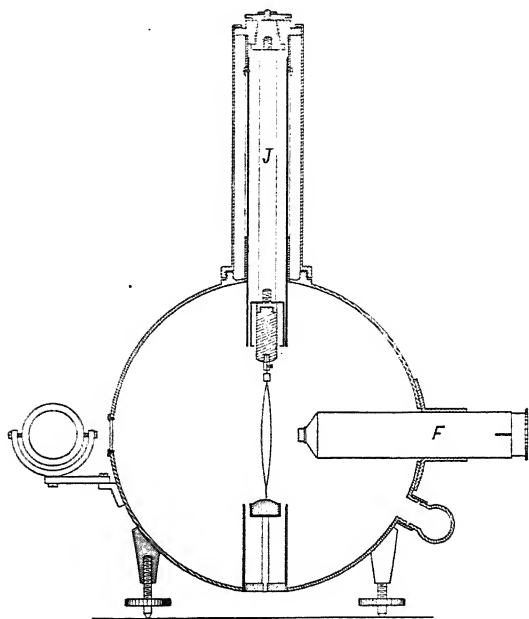
Fig. 9.—Wulf's radiation apparatus.

The charging method is, so to say, the converse of the method just described ; in it the vessel itself is charged to several hundred volts by connection to a constant source of potential, while the inner electrode and electrometer are earthed at the beginning of the measurement. As soon as the earth connection is broken the needle or thread of the electrometer begins to move in accordance with the number of ions reaching the inner electrode ; the rate of

charge (plus the insulation correction) corresponds exactly to the term dV/dt of the previous formula.

The measurement itself is relatively simple, though the current intensities in question are exceedingly small. An ionising power $q = 10$ I (*i.e.*, ten pairs of ions produced per cubic centimetre per second) corresponds, in an ionisation vessel of 1 litre volume, to a current of only $1·6 . 10^{-15}$ amp.

In order to obtain the greatest possible voltage loss in the system at a given small natural ionisation it is necessary either to make the electrical capacity as small as possible or to choose as large a volume as possible for the vessel. The effect may also be increased by filling the vessel with a denser gas than ordinary air, or by compressing the air. The inner wall of the vessel is also sometimes covered with a coating of a metal of high atomic weight, in order to increase the ionisation effect by means of the secondary radiation thus produced.

Fibre electrometers are almost exclusively used for portable apparatus, especially the Wulf two-fibre electrometer. The ionisation vessel itself must be filled with dust-free dry air (or other gas) which is free from radioactive substances. The apparatus constructed by Th. Wulf [1] has proved particularly convenient; in this instrument the cylindrical vessel of the electrometer itself forms the ionisation chamber, the charged pair of fibres being fixed in the middle of the chamber and serving as the inner electrode. The total capacity is reduced in this way to about 1 cm. Fig. 9 shows a vertical section of Wulf's radiation apparatus. The distance of the two fibres, which is proportional to the voltage of the system, is measured by means of the ocular micrometer in the microscope F. The fibres are illuminated from behind by mirror a. In order to allow the insulation loss to be determined separately, a metal cylinder J, fitting fairly closely round the fibre system, is built into the instrument

[1] *Phys. Zeitschr.*, **10,** 152, 997 (1909).

in such a way that it may be let down over the fibres during an insulation test so as to separate them from the rest of the ionisation chamber. The apparatus, when closed, is completely air and watertight, so that it may also be employed for absorption experiments under water. The fibre system is charged by means of a lever, not visible in the diagram, which can be operated from outside. The apparatus was made more rigid by Günther and Tegetmeyer (Brunswick) for use in balloons, and was pro-
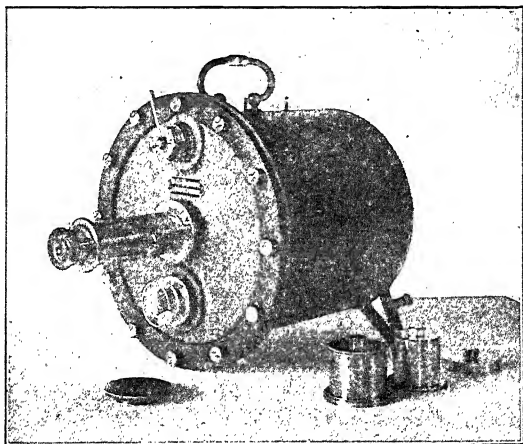
Fig. 10.—Radiation apparatus with loop system (Kolhörster).
(*Phys. Zeitschr.*, **27**, 62, 1926. S. Hirzel, Leipzig.)

vided with temperature compensation. Further important improvements for balloon ascents were devised by Kolhörster.[1] The mechanical charging lever was replaced by a magnetic charging device, and the resistance of the apparatus to differences of air pressure was increased, while the slight sensibility to temperature variations still present was eliminated.

Quite recently a radiation apparatus has been con-

[1] *Phys. Zeitschr.*, **14**, 1066; *Abh. Naturf. Ges. Halle*, 1913, No. 5 1914, No. 4; *Zeitschr. f. Phys.*, **5**, 107 (1921).

structed by the same author,[1] in which the electrometric system consists of what he describes as a double-loop electrometer (Figs. 10 and 11 [2]).   Two similar loops of
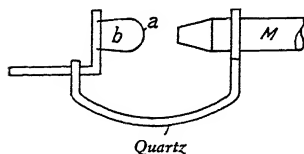
FIG. 11.—Loop electrometer (Kolhörster).

metal-coated quartz fibre are fixed close and parallel to one another vertically on the two sides of a small metal plate, so as to be free to move.   (In the accompanying figure only one loop is, of course, visible.)   The distance apart of the two ends of the loops nearest the microscope (*a* in the figure) is measured with an eyepiece micrometer, and is proportional to the applied potential.

The loop system is fixed firmly to the tube of the microscope by means of a bent quartz tube, so as to ensure that the position of the fibres is unaffected by temperature.   The system of loops, in connection with an aluminium wire, forms the inner electrode of an ionisation cylinder of 4 litres capacity. The electrical capacity of the whole instrument only amounts to 0·4 cm.

As a non-portable instrument, that of G. Hoffmann [3] is particularly worthy of mention. The ionisation chamber itself is formed by three wire rings cutting one another perpendicularly ; in the middle of the spherical space thus formed
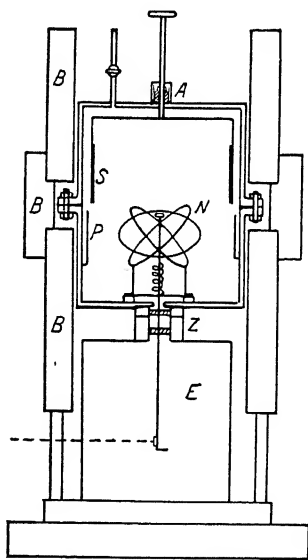
FIG. 12.—G. Hoffmann's apparatus.

[1] *Zeitschr. f. Instr.-Kunde*, **44**, 334, 494 (1924) ; *Phys. Zeitschr.*, **27**, C2 (1926).

[2] From *Phys. Zeitschr.*, **27**, 62 (1926).   (Hirzel, Leipzig.)

[3] *Zeitschr. f. Phys.*, **25**, 177 (1924).

is placed the inner electrode, connected to an electrometer specially constructed by the same author. The wire ring system itself is placed in the middle of a large, airtight metal chamber; the radiation from the walls of the chamber is practically zero inside the charged-ring system (see Fig. 12), so that the residual radiation of the apparatus is extremely small. By surrounding it with thick metal shields B, the whole apparatus can be so well protected from the ordinary γ-radiation of the surroundings that the ionisation inside is almost entirely due to the cosmic ultra-gamma radiation (*höhenstrahlung*). The apparatus is particularly used for the photographic registration of this radiation.

Other forms of registering apparatus for penetrating radiation have been devised by A. Gockel,[1] K. Bergwitz,[2] R. A. Millikan, and J. S. Bowen.[3] A specially accurate method was developed for measurements on board ship by W. F. G. Swann.[4]

3. The Total Radiation and its Components.—As has been said, the ionisation observable in a closed vessel consists of four components. We will describe the ionising power of each of the four factors by the following symbols:

(1) Residual radiation (wall radiation)   . q_0
(2) Atmospheric radiation   .   .   . q_A
(3) Earth radiation   .   .   .   . q_E
(4) *Höhenstrahlung* (ultra-gamma radiation) q_H

The figures q_0, q_A, etc., represent the numbers of pairs of ions produced per cubic centimetre per second in the vessel by the respective sources of radiation. The symbol I will again be used, for the sake of brevity, to represent " pairs of ions per cubic centimetre per second." Thus,

[1] *Phys. Zeitschr.*, **16**, 345 (1915).

[2] *Elster-Geitel-Festschr.*, p. 585, Brunswick, 1915.

[3] *Phys. Rev.* (2), **22**, 198 (1923).

[4] Research Department of Terr. Magn., Carnegie Inst. of Washington, III., No. 175 (1918).

for example, $q_0 = 3$ I means $q_0 = 3$ pairs of ions per cubic centimetre per second. The total radiation is simply the sum of the four components

$$q = q_0 + q_A + q_E + q_H.$$

It must be noted that in the individual values of q the effect of the secondary radiation produced on the walls by the primary radiation is included. In order to obtain the action of the single components in the free atmosphere it is necessary to determine the action of the secondary radiation by special experiments, so as to be able to subtract it from the total effect observed.

If a material is chosen for the walls which is as free as possible from radioactive impurities, the value for the total radiation (usually measured in zinc vessels) in different places varies between $q = 4$ I and $q = 20$ I.

In order to determine the individual components of the total radiation, recourse must be had chiefly to experiments under conditions in which one or another of the components is almost entirely absent.

If it is wished to eliminate the atmospheric radiation, the apparatus must be protected from above with ice blocks or layers of water of sufficient thickness so that the γ-rays of the radioactive substances in the air are not able to penetrate. Metal shields are also useful, provided that they are free from radioactive impurities. A lead cover of 7 cm. thickness reduces the action of the γ-rays of radium C to about 1 per cent. As a shield against earth radiation, the shields must be placed beneath the apparatus. (Placing the apparatus immediately over a water surface fulfils the same purpose.) Finally, in order to cut out the cosmic *höhenstrahlung* completely, the apparatus must be surrounded on all sides by a layer of ice or water of 10 to 15 metres thickness. The ionisation still observed in this case then corresponds to the residual radiation q_0. The numerical values given in the following pages are

based on the usual value for the elementary charge, $e = 4 \cdot 77 \cdot 10^{-10}$.

4. Residual Radiation (Wall Radiation).—When the metal is carefully chosen and purified, the lowest value of the residual radiation observed, as a rule, in zinc vessels is $q_0 = 2$ to 4 I. Still lower values are at times obtained, but are exceptional; thus Bergwitz (*loc. cit.*, p. 123) registered a value $q_0 = 0 \cdot 8$ I in the rock-salt mines at Hewigsburg, 400 metres underground, where the zinc vessel was surrounded on all sides by layers, at least 100 metres thick, of the quite inactive rock-salt. Hoffmann,[1] by shielding with inactive lead, obtained $q_0 + q_H = 1$ I.

The following factors come into consideration as possible causes of the residual ionisation in closed vessels.

(*a*) *Contamination of the Gas within the Vessel or of the Material of the Walls by Emanation and other Radioactive Substances.*—It must be remarked that the α-radiation from the average amount of radium emanation in the free air (10^{-16} curie/c.c.), together with its decomposition products, is sufficient to produce an ionisation of $1 \cdot 2$ I. If thorium products are also present, the effect may easily amount to 2 I or more. In order to exclude the influence of this effect entirely, it is sufficient to leave the gas in the carefully-closed vessel for a month or so, since in this time the radium emanation will have decomposed completely. It is much more difficult to reduce the quantity of radiation due to the radioactive impurities in the metal walls. The sensitive method of G. Hoffmann for registering ionisation, already mentioned, allows of the recognition of the emission of single α-particles in the presence of the simultaneous effect of the β- and γ-rays. Hoffmann [2] found that radioactive impurities occur in all metals, both on the surface and within the body of the metal. Zinc, on account of its method of manufacture,

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[1] *Elster-Geitel-Festschr.*, p. 435, Brunswick, 1915; *Ann. d. Phys.* (4`, **62,** 738 (1920).

[2] *Zeitschr. f. Phys.*, **7,** 254 (1921); **25,** 177 (1924).

seems to contain particularly small quantities of such impurities. Copper and brass frequently contain appreciable quantities of radioactive impurities, apparently resulting from the metallurgical process which it has undergone in manufacture. Vessels of steel and, for many experiments, chambers of fresh-water ice have given good results. Slight radioactive contamination of the material of the walls must in any case be regarded as the chief source of the residual radiation. Etching and scouring of the surface of the metal often reduce the residual radiation quite appreciably.

(b) *Specific Activity of the Material of the Wall.*—In the present state of our knowledge of the constitution of the chemical elements and of matter in general, the possibility of a very slow radioactive decomposition of all the elements cannot be entirely excluded. Definite evidence of a specific activity has only been found so far by Hoffmann in the case of platinum. In general, experiment has up to the present given no proof of a spontaneous decomposition of ordinary metals.

(c) *Ionisation by Molecular Collision.*—A number of authors—K. Bergwitz,[1] G. C. Simpson and C. S. Wright,[2] P. Langevin and J. J. Rey,[3] McLennan and A. R. McLeod,[4] M. Wolfke,[5] K. H. Kingdon,[6] F. v. Hauer[7]— have dealt theoretically and experimentally with the question of whether the very high velocities attained by some of the molecules in consequence of their thermal motion are sufficient to produce ions by collision with other molecules. The rapid increase of the residual ionisation with temperature which must be expected if

[1] *Habilit.-Schrift,* Brunswick, 1910.
[2] *Proc. Roy. Soc.,* A, **85**, 175 (1911).
[3] *Le Radium,* **10**, 142 (1913).
[4] *Phil. Mag.* (6), **26**, 740 (1913).
[5] *Le Radium,* **10**, 137 ; *Phys. Zeitschr.,* **18**, 34 (1917).
[6] *Phil. Mag.* (6), **32**, 190, 397 (1916).
[7] *Phys. Zeitschr.,* **17**, 583 ; **18**, 98 (1916–17).

this is so has not been detected (Patterson,[1] A. Devik,[2] C. H. Kunsman [3]).   Theoretical investigations did not lead to quite concordant results.   It can, however, be regarded as certain that at room temperature the ionisation effect due to molecular collision is far smaller than the observed residual ionisation.   Since the smallest experimentally observed value of the latter at room temperature (0·8 I) is some ten times smaller than the total effect of the penetrating radiations, the spontaneous ionisation of gases by molecular collision can only play a quite subordinate *rôle* in such measurements.

5. Atmospheric and Earth Radiation.—The ionising powers q_A and q_E of these two components may be determined both by calculation and experiment.   When the concentrations of radioactive substances in the earth and in the air are known, together with the absorption coefficients of the γ-rays in the earth and in air, the effect of the γ-radiation in an ionisation vessel set up near the ground may be calculated by integration of the action in the air space and in the earth (see A. S. Eve,[4] W. W. Strong,[5] K. Kurz,[6] Simpson and Wright (*loc. cit.*, p. 126), V. F. Hess,[7] W. Kolhörster [8]).

The decomposition products of the radium emanation in the air give an ionisation of 0·1 I.   Estimating the activity of the thorium and actinium products in the air near the ground at the same figure, the atmospheric radiation effect amounts to

$$q_A = 0\cdot2 \text{ I.}$$

If we assume the average radium content of the uppermost layer of earth (alluvium) to be $1\cdot2 \, . \, 10^{-12}$ gm. per

[1] *Phil. Mag.* (6), **6,** 231 (1903).

[2] *Sitz.-Ber. Heidelb. Ak. d. W.,* **24** (1914).

[3] *Phys. Rev.* (2), **16,** 349, 366 (1920).

[4] *Phil. Mag.* (6), **12,** 189 (1906) ; **21,** 26, and **22,** 551 (1911).

[5] *Phys. Zeitschr.,* **9,** 117 (1908).

[6] *Phys. Zeitschr.,* **10,** 834 (1909).

[7] *Wien. Ber.,* **122,** 1481 ; *Phys. Zeitschr.,* **14,** 1002 (1913).

[8] *Abh. Naturg. Ges. Halle* (N.F.), 1914, No. 4.

gram of soil, and take the proportion of the γ-radiation of the thorium products and of uranium X_2 in the soil as equal to that of the radium products, the total earth-radiation effect becomes approximately

$$q_E = 2 \cdot 7 \text{ I.}$$

Over primitive rock more rich in radium the value of q may, of course, rise to more than 10 I. This estimate agrees surprisingly well with experimental determinations by Hess [1] and by Kolhörster [2] on alluvial sites at Vienna and at Waniköi (Turkey), which gave the value $2 \cdot 5$ I for the earth radiation.

It has also been thought possible that the radioactive products deposited on the surface of the earth, or the apparatus itself, and on its surroundings, by the normal action of the earth's electric field on the positively-charged atoms of radium A and thorium A might account for a part of the earth radiation (" *surface radiation* "). A calculation by Schweidler [3] shows, however, in agreement with the estimates of Simpson and Wright (*loc. cit.*, p. 126), that this surface action can only amount to $0 \cdot 04$ I at the most.

Summarising, it may be said that the earth radiation amounts to 2 to 10 I, according to the nature of the ground, while the atmospheric radiation is only $0 \cdot 2$ I on the average. Both components vary with time and locality. The earth radiation may be influenced by increase or diminution of the amount of emanation emerging from the uppermost layers of the soil (soil respiration).

The absorption of earth radiation in the soil and the atmosphere has been calculated by L. V. King.[4] It appears that at a height of 50 metres the earth radiation sinks to 49 per cent. of the surface value, at 83 metres to

[1] *Phys. Zeitschr.*, **14,** 610 (1913).
[2] *Zeitschr. f. Phys.*, **11,** 379 (1921).
[3] *Wien. Ber.*, **122,** 137 (1913).
[4] *Phil. Mag.* (6), **23,** 242 (1912) ; **26,** 604 (1913).

33 per cent., at 167 metres to 15 per cent., and at 333 metres to 3·7 per cent.

Experimental determinations of the earth radiation apart from the residual radiation have been made in many localities since the pioneer investigations of Th. Wulf.[1] The simplest method of carrying out the determination is first to measure the total radiation at the surface of the ground with such an apparatus as that of Wulf, and then to sink the apparatus in the ground so that it is surrounded on all sides by earth. In the second experiment the earth radiation is about twice as great, and therefore, since the atmospheric radiation only accounts for about 0·2 I on the average, the difference in the ionising powers in the two cases gives fairly accurately the value of the earth radiation at the particular place. Another method, which is still more often used, consists in setting up the apparatus first over land, and then over a water surface near by, such as a lake or pond. The diminution in the total radiation always observed over water is due to the absence of earth radiation. The γ-radiation of the radioactive substances contained in fresh or sea water may be entirely neglected in most cases. The following table gives some of the results of such measurements of earth radiation:

Observer.	Place.	Earth Radiation, q_E.
Schweidler	Seeham (Upper Austria)	1·9 to 4·0 I
J. C. McLennan	Toronto (Canada)	5·3 I
Simpson and Wright	Matjesfontein (South Africa)	7·9 I
Kunsman	California	4·5 I
L. A. Bauer and Swann	Washington, D.C. (U.S.A.)	4·0 I
V. F. Hess	Vienna	2·5 I
W. Kolhörster	Waniköi (Turkey)	2·5 I
Schweldler	Innsbruck (Tyrol)	12·0 to 14·0 I

The earth radiation may vary within wide limits according to the geological formation of the rock over which the apparatus is set up. V. Oberguggenberger [2]

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[1] *Phys. Zeitschr.*, **10,** 997 (1909).

[2] *Wien. Ber.*, **132,** 59 (1923).

found the earth radiation over dolomite to be 0·6 to 7·5 I, over Muschelkalk 2 to 4 I, over lias limestone 1·3 I, in good agreement with the values to be expected from the radium and thorium content of these minerals.   The average value of the earth radiation in ionisation vessels of zinc, therefore, amounts to 2 to 4 I.   In the free atmosphere the effect would be less, in the proportion of 4 : 5·5, according to the investigations of A. S. Eve [1] and V. F. Hess,[2] since the secondary radiation from the zinc wall would then be absent.   The earth radiation at one and the same place is subject to considerable variations, due to changes in the concentration of emanation or its products in the first metre of thickness of the ground (Wulf).

Most observers have found definite evidence of a yearly —in many places also of a daily—period of variation of the radiation.   The maximum occurs at the warm season of the year, the minimum in the first months of the year. The amplitude amounts to 1·5 I at Freiburg, Switzerland (Gockel [3]) ;   0·3 I at Kolberg, Prussia (K. Kähler [4]) ;   and 0·5 I at Waniköi, Turkey (Kolhörster, *loc. cit.*).   On the 2,000-metre peak of the Obir (Carinthia) the amplitude of the variation is also only 0·5 I (Hess and M. Kofler [5]). The daily period, when present, varies from place to place. On account of the small variability of the earth radiation, the atmospheric radiation may cause complications in the measurement of the amplitude of the total radiation in places where the emanation content of the air is high.   In most localities the day and night values of the total radiation show no difference.   Kolhörster [6] has made the

[1] *Phil. Mag.*, **27**, 394 (1914).

[2] *Wien. Ber.*, **122**, 1481 (1913).

[3] *Phys. Zeitschr.*, **16**, 345 (1915) ;   *Neue Denkschr. Schweizer Naturf. Ges.*, **53**, No. 1 (1917).

[4] *Phys. Zeitschr.*, **21**, 324 (1920).

[5] *Phys. Zeitschr.*, **18**, 385 (1917).

[6] *Zeitschr. f. Phys.*, **11**, 379 (1922).

closest analysis of the daily variations of the total radiation at Waniköi. At this place the radiation varies inversely with the change in the atmospheric pressure. The other variations of total radiation which are connected with meteorological factors are to be ascribed to changes in the earth and atmospheric radiations, which are connected with the passage of emanation from earth to atmosphere and depend on the permeability of the earth.

It must also be mentioned that precipitates may occasion temporary increases in the radiation at the surface, bringing down radioactive decomposition products ; this has been proved by numerous observers. Gockel (*loc. cit.*, p. 130) found on one occasion, when the apparatus was completely covered with snow during a thunderstorm on the Jungfrau Ridge, an increase in the radiation of 2 I.

6. The Cosmic Ultra-Gamma Radiation (*höhenstrahlung*). —(*a*) *Observations on Towers and Mountains, and in Flying Machines.*—As has been mentioned in the Introduction, observations on towers have shown a decrease in the total radiation (of 1 to 3 I),[1] though not of the amount first expected. Th. Wulf,[2] in Paris, found a value on the ground of 6 I, after subtraction of the residual radiation, and of 3·5 I on the Eiffel Tower at a height of 300 metres. Wulf concluded from these experiments that either there existed another source of γ-rays in the upper layers of the atmosphere, or that the absorption of the γ-rays in the air must be considerably smaller than had hitherto been assumed. The observations on towers could not give a definite solution, on account of the complication introduced by the masonry or iron of the tower, which might itself either emit radiation or exert a screening action,

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[1] J. C. McLennan (and Macallum), *Phys. Zeitschr.*, **8**, 556 (1907); *Phil. Mag.* (6), **22**, 639 (1911) ; K. Bergwitz, *Habilitationsschr.*, Brunswick, 1910, and *Elster-Geitel-Festschr.*, Brunswick, 1915.

[2] *Phys. Zeitschr.*, **11**, 811 (1910).

according to the particular circumstances of the case. Recourse was, therefore, had to balloon observations. The first four ascents (Bergwitz, Gockel, see references § 23 (1)) led to indefinite results.   Gockel's observations give a slight increase in the radiation at heights of 2 to 3 km., when they are reduced to normal pressure in the ionisation chamber.   Direct measurement of the absorption coefficient of the γ-rays of radium C by V. F. Hess [1] showed that the absorption actually occurs as quickly as was expected, so that the earth radiation must consequently be quite inactive at heights of only a few hundred metres.

Ten balloon ascents by Hess (*loc. cit.*, § 23 (1)) with improved apparatus led to the decisive result already mentioned in the Introduction : a slight decrease of the total radiation up to 1,000 metres, then a slow, and finally a rapid, increase of the radiation. *From this Hess assumed the existence of a hitherto unknown radiation entering the atmosphere from above, of greater hardness than the known γ-rays (höhenstrahlung* or ultra-gamma rays).[2] The numerical results are given in the following table, together with the radiation values, up to 9 km., obtained later by Kolhörster [3] with further improved instruments.

L. V. King [4] suggested that the increase of radiation with height was due to the radioactive deposits precipitated on the balloon during the ascent.   This objection was shown to be unfounded by measurements of the radiation over the surface of the balloon made immediately on landing (Hess).   Calculations of Schweidler also led to the same result (*loc. cit.*, p. 128).

[1] *Phys. Zeitschr.*, **12**, 998 (1911).

[2] The name ultra-gamma-rays was provisionally suggested by Hess (*Phys. Zeitschr.*, **27**, 159, 1926).

[3] *Verh. d. Deutsch. Phys. Ges.*, **16**, 719 (1914) ; *Phys. Zeitschr.*, **14**, 1066, 1153 (1913).

[4] *Phil. Mag.*, **23**, 242 (1912).

Height above Sea Level.	Mean Difference of Ionisation compared with Surface Value.		Height above Sea Level.	Mean Difference of Ionisation compared with Surface Value. Kolhörster, 1913–14.
	Hess, 1911–12.	Kolhörster, 1913.		
0·5 km.	— 1·1	— 1·7 I	5·5 km.	+ 22·1 I
1·0 ,,		— 1·5 I	6·0 ,,	+ 28·0 I
1·5 ,,	0·0	+ 0·4 I	6·5 ,,	+ 37·0 I
2·0 ,,		+ 1·0 I	7·0 ,,	+ 45·2 I
2·5 ,,	+ 1·3	+ 2·6 I	7·5 ,,	+ 54·0 I
3·0 ,,		+ 4·2 I	8·0 ,,	+ 62·5 I
3·5 ,,	+ 4·0	+ 5·8 I	8·5 ,,	+ 71·0 I
4·0 ,,	—	+ 9·1 I	9·0 ,,	+ 79·0 I
4·5 ,,	+ 16·3	+ 11·8 I	9·3 ,,	+ 85·0 I
5·0 ,,	(up to 5,400 m.)	+ 16·2 I		

In the foregoing table only differences between the ionising powers at the given altitudes and on the ground are given, since these figures show most clearly the initial decrease and subsequent increase in the radiation with height. The figures are mean values from parallel observations with several sets of apparatus. Since the earth radiation may be taken as zero after 1,000 metres and the atmospheric radiation is very small, the figures given may be regarded as intensities of the *höhenstrahlung* at the various heights after adding to them the value of the *höhenstrahlung* on the earth's surface (1 to 2 I) as determined by experiments to be described later.

After the discovery and verification of the existence of the cosmic *höhenstrahlung* by the balloon experiments just described, a number of authors carried out experimental investigations on the subject. Gockel[1] found values of 3 to 4 I for the *höhenstrahlung* over glaciers at heights of 2,800 to 3,400 metres; Kleinschmidt obtained similar figures with kites flown over Lake Constance. Oberguggenberger (*loc. cit.*, p. 129) obtained the value 2·5 I for the *höhenstrahlung* on a mountain at 2,000 metres,

[1] *Phys. Zeitschr.*, **16**, 345 (1915).

and 4·7 I at 2,900 metres, while Kolhörster [1] obtained on the Jungfrau Ridge (3,500 metres) the value 5·3 I.   H. Marsden [2] was unable to find any increase in the radiation at 2,800 metres on an extinct volcano in New Zealand. As the earth radiation was not measured separately on this occasion, it is very likely that differences in this radiation at the foot and summit of the mountain masked the increase of the *höhenstrahlung* (ultra-gamma radiation).

In America experiments have been made by R. A. Millikan and his pupils, R. M. Otis, Harvey Cameron, and J. S. Bowen.[3] Millikan and Bowen [4] succeeded in sending two pilot balloons with recording apparatus to heights of 11 and $15\frac{1}{2}$ km.   The latter ascent gave a mean value of q_H = approx. 30 I from 5 to 15 km. and back again ; according to Kolhörster's curve for 10 km., a value about three times as great is to be expected.   Since, however, Millikan and Bowen themselves state that their instrument was not entirely independent of temperature, it appears that the value obtained by them may not be correct, particularly as K. Büttner,[5] in an aeroplane ascent to 7 km., obtained from two sets of apparatus the same curve for the increase of the ultra-gamma radiation as Kolhörster ; at 7 km. q_H was 39 I.   Observations in aeroplanes and on mountains by the above-named American investigators up to 4 and 5 km. also confirmed the increase in the radiation, the agreement with the results of European measurements in general being good.

From the foregoing observations in the free air and on mountains the existence of the cosmic ultra-gamma-rays may be taken as definitely proved.

(*b*) *Observations of the Ultra-Gamma Radiation at the Surface of the Earth.*—In 1909, from simultaneous observation

[1] *Sitz.-Ber. Preuss. Ak. d. Wiss.*, **34**, 366 (1923).
[2] *Terr. Magn.*, **27**, 105 (1922).
[3] *Phys. Rev.* (2), **22**, 198, 199 ; **23**, 778 (1923–24) ; *Nature*, **114**, 143 (1924) ; *Phys. Rev.* (2), **28**, 851 (1926).
[4] *Phys. Rev.* (2), **22**, 198 (1923) ; **27**, 353 (1926).
[5] *Zeitschr. f. Geophysik.*, **2**, 254 (1926).

of the penetrating radiation on the sea both above and below the water, Pacini [1] had been led to assume the existence of some other source of γ-rays besides the radioactive substances in the earth and air. The strength of the ultra-gamma radiation at sea level may be determined by "shielding" experiments, *i.e.*, by simultaneous measurements of the radiation under and above water and in ice caves. Older experiments of this kind are doubtful, since at the time they were made the extraordinary penetrating power of the ultra-gamma rays was not realised. According to the experiments and calculations of Schweidler,[2] Kolhörster,[3] and Gockel,[4] the ionising power of the ultra-gamma radiation at sea level amounts to 1 to 2 I. Hoffmann [5] obtained in his photographic records at Königsberg the value $q_0 + q_H = 1 \cdot 0$ I.

(*c*) *Experiments at High Pressures.*—The first investigations of the influence of the pressure of the gas on the ionisation in closed vessels gave quite irregular results, which varied according to the relative intensities of the four components of the radiation in the vessel in question. We will therefore confine ourselves to a discussion of the newer experiments carried out, on the suggestion of W. F. G. Swann,[6] by K. Melvina Downey [7] and Hal F. Fruth,[8] under such conditions that, apart from the very small residual radiation, only the ultra-gamma radiation was able to cause ionisation in the vessel. The earth radiation was excluded partly by placing the apparatus

[1] *Rend. Accad. Lincei* (5), **18**, 1, 123 (1909) ; *Le Radium*, **8**, 307 (1911).

[2] *Wien. Ber.*, **121**, 1297 (1912) ; **122**, 137 (1913) ; **126**, 1009 (1917) ; *Elster-Geitel-Festschr.*, Brunswick, 1915.

[3] *Phys. Zeitschr.*, **14**, 1066 (1913) ; *Zeitschr. f. Phys.*, **11**, 379 (1922) ; see also *Ber. Preuss. Ak. d. Wiss.*, **34**, 366 (1923).

[4] *Loc. cit.*, p. 133.

[5] *Phys. Zeitschr.*, **25**, 177 (1924) ; **26**, 40 (1925).

[6] *Bull. Nat. Res. Council, Amer. Geophys. Union*, Rept., **17**, 65 (1922).

[7] *Phys. Rev.* (2), **16**, 420 (1920) ; **20**, 186 (1922).

[8] *Phys. Rev.* (2), **22**, 109 (1923).

under water, and partly by thick concrete walls. The experiments were carried out with the vessel filled to pressures of 80 atmospheres with air, nitrogen, oxygen and carbon dioxide, carefully aged so as to be free from emanation. The ionisation at first rises proportionally with the pressure up to about 30 atmospheres, and then by about 1 I for every atmosphere rise in pressure. With nitrogen, and with a mixture of 4 parts nitrogen and 1 part oxygen, the increase persists up to the highest pressures, but with the other gases a limiting value of the ionisation is finally reached. This behaviour is at present not explained. Swann concluded from the experiments, with some reservation, that considerably less than 1 I of the ionisation at sea level and atmospheric pressure is directly or indirectly due to the *höhenstrahlung*. Fairly similar results have recently been obtained at pressures up to 75 atmospheres by James W. Broxon.[1] With certain assumptions as to the quality of the hard and soft secondary rays developed by the primary radiation at the walls of the vessel and in the gas, theoretical curves may also be deduced [2] which agree well with the curves found experimentally for the increase in ionisation with pressure.

According to a preliminary communication by W. F. G. Swann,[3] other measurements on Pike's Peak (Colorado) at a height of about 4 km., in a thick-walled iron vessel at high pressure, showed an increase of only 0·75 I per atmosphere.

(d) *The Absorption Coefficient of the Ultra-Gamma Radiation.*—On the assumption that the new radiation is absorbed according to an exponential law, like the γ-rays of radioactive substances, the absorption coefficient may easily be calculated from the curve showing the

[1] *Phys. Rev.* (2), **27**, 542 (1926).

[2] *Phys. Rev.* (2), **28**, 1071 (1926).

[3] *Bull. Amer. Phys. Soc.*, Vol. I., No. 12, December, 1926, p. 14.

increase of this ultra-gamma radiation with height. If it is assumed that these rays are coming in a parallel beam (source far distant), the strength of ionisation in the atmosphere will decrease downwards, and after passing through a layer of thickness d the ionisation will be given by the expression

$$q_d = q_\circ \cdot e^{-\mu d},$$

where μ is the absorption coefficient of the new radiation. Calculations of Kolhörster,[1] Schweidler[2] and Seeliger[3] yield values for the absorption coefficient between 0·5 and $1·0 \cdot 10^{-5}$ cm.$^{-1}$, according to the assumptions made as to the origin of the new source of radiation (cosmic space or uppermost layers of the atmosphere); direct measurements by Hess of the absorption coefficient of the ordinary γ-rays of radium C gave a value of $4·5 \cdot 10^{-5}$ cm.$^{-1}$. The ultra-gamma rays are, therefore, really much more penetrating than the γ-rays. The first measurements of the absorption of the ultra-gamma rays in water were probably those of Gockel (*loc. cit.*, p. 133). Specially careful determinations of the absorption of this radiation in water and ice have recently been made by Kolhörster[4]; they gave a mean value for μ (in water) of $2·2 \cdot 10^{-3}$ cm.$^{-1}$, while the absorption coefficient for the γ-rays of radium C is $3·9 \cdot 10^{-2}$ cm.$^{-1}$. Thus, while the latter are reduced to one-half by a layer of water 18 cm. thick, the same reduction does not occur with the ultra-gamma radiation until a thickness of more than 300 cm. is reached. These and other recent measurements of the absorption coefficient of the ultra-gamma rays in water by Millikan and Cameron, Myssowsky and Tuwim, Büttner, and Swann are collected in the following table:

[1] *Abh. d. Naturf. Ges. Halle* (N.F.), 1914, Nr. 4; *Verh. d. D. Phys. Ges.*, **16,** 719 (1914).

[2] *Elster-Geitel-Festschr.*, Brunswick, 1915, p. 411.

[3] *München. Sitz.-Ber.*, **1** (1918).

[4] *Sitz.-Ber. Preuss. Ak. d. W.*, **34,** 366 (1923); *Zeitschr. f. Phys.*, **36,** 147 (1926).

Absorption Coefficients of the Ultra-Gamma Radiation.

Observer.	Absorbing Medium.	Calculated by	μ_{H_2O} in cm.$^{-1}$
Kolhörster . . 0–9,300 m.	Air.	Kolhörster, 1914 [1] .	$5\cdot5\,.\,10^{-3}$
,, . . 0–9,300 m.	,,	v. Schweidler, 1915 [2] .	$5\cdot8\,.\,10^{-3}$
,, . . 0–9,300 m.	,,	Linke, 1916 [3] .	$3\cdot6\,.\,10^{-3}$
,, . . 0–9,300 m.	,,	Seeliger, 1918 [4] .	$3\cdot8\,.\,10^{-3}$
Kolhörster 2,300–3,550 m.	Air.	Kolhörster, 1923 [5] .	$2\cdot6\,.\,10^{-3}$ ⎫
,, . . 2,300 m.	Ice.	,, ,,	$1\cdot6\,.\,10^{-3}$ ⎬ Mean,
,, . . 3,550 m.	,,	,, ,,	$2\cdot7\,.\,10^{-3}$ ⎱ $2\cdot2\,.\,10^{-3}$
,, . . . 40 m.	Water.	,, ,,	$2\cdot0\,.\,10^{-3}$ ⎭
Millikan . . 1,400 m.	Water.	Millikan, 1925 [6] .	$1\cdot8$–$3\cdot0\,.\,10^{-3}$
,, . . 3,900 m.	,,	Millikan and Cameron [6]	$1\cdot8$–$3\cdot0\,.\,10^{-3}$
Myssowsky and Tuwim 30 m.	Water.	Myssowsky and Tuwim, 1925.[7]	$3\cdot6\,.\,10^{-3}$
Büttner . . . 80 m.	Water.	Büttner [8] . .	$2\cdot5\,.\,10^{-3}$
,, . 80–6,300 m.	Air.	,, . .	$3\cdot3\,.\,10^{-3}$
W. F. G. Swann . 0–4,000 m.	Air.	W. F. G. Swann[9]. .	$4\cdot2\,.\,10^{-3}$

The absorption coefficient of the *höhenstrahlung* in water is thus from 2 to 3.10^{-3}, and therefore some fifteen times smaller than the absorption coefficient of the γ-radiation of radium C ($3\cdot9\ .\ 10^{-2}$).

G. Hoffmann [10] concluded, from absorption measurements carried out at sea level with thick layers of lead, that at that height no appreciable amount of a radiation of greater penetrating power than the γ-rays was present. The fact that this is contradicted by absorption experiments with water and ice led him to the conclusion that in substances consisting of elements of low atomic weight

[1] *Abh. d. Naturf. Ges. Halle* (N.F.), No. 4, 1914.

[2] *Elster-Geitel-Festschr.*, Brunswick, 1915, p. 411.

[3] *Meteorol. Zeitschr.*, **33,** 157 (1916).

[4] *München. Ber.*, 1918, p. 1.

[5] *Berliner Ber.*, 1923, p. 366.

[6] *Scientific Monthly*, December, 1925, p. 661; *Proc. Nat. Acad. of Sc.*, **18,** 48 (1926); *Phys. Rev.* (2), **28,** 851 (1926).

[7] *Zeitschr. f. Phys.*, **35,** 299 (1925).

[8] *Zeitschr. f. Geophys.*, **2,** 254 (1926), from Angenheister, " Atmosph. Elektr.," in Geiger and Scheel's "Handb. d. Physik," XIV. (1926), p. 433.

[9] *Bull. Amer. Phys. Soc.*, Vol. I., No. 12, December, 1926, p. 14.

[10] *Phys. Zeitschr.*, **26,** 669 (1925).

the scattering of the ultra-gamma rays is considerably greater than the true absorption, the latter being exceedingly small in water and air. This would lead to the conclusion that the most minute amounts of radium, etc., in water would cause appreciable ionisation in closed vessels submerged in it. Serious objections to this conclusion of Hoffmann's have been advanced by V. F. Hess.[1]

It must, however, be admitted that, in view of the impossibility, in practice, of completely separating the processes of scattering and true absorption, the values of the absorption coefficients of the ultra-gamma radiation given above are to be regarded as somewhat uncertain.

Quite recently G. Hoffmann,[2] using extremely sensitive apparatus, has been able to show that at sea level a fraction of the radiation is not reduced to half its value until it has passed through 70 cm. of lead. From these measurements the value of the absorption coefficient for the hardest portion of the radiation would amount to $\mu_{(H_2O)} = 0.9 \cdot 10^{-3}$ cm.$^{-1}$, a still smaller value than that given above. The *höhenstrahlung* is not homogeneous, *i.e.*, it consists of components of widely-differing wavelengths and absorption coefficients. This is seen particularly clearly from the measurements of K. Büttner,[3] of Kolhörster, and of Millikan and Cameron (*loc. cit.*, p. 138). The latter authors, in experiments under the surface of a lake formed of molten snow at a height of 3,900 metres, found a diminution in the ionisation in their apparatus to a depth of 15 metres. They showed that the absorption curve did not correspond to that of a homogeneous radiation. Just as in the well-known Compton effect with Röntgen rays, there is a gradual transformation of the primary radiation into secondary, tertiary, etc., radiation

[1] *Phys. Zeitschr.*, **27**, 159 (1926).

[2] *Ann. d. Phys.* (4), **80**, 780–807 (1926); *Die Naturwiss.*, **14**, 1004 (1926).

[3] *Zeitschr. f. Geophys.*, **2**, 187, 251, 291 (1926).

of greater wavelength, and therefore smaller frequency; in addition, secondary β-rays of high velocity are produced in the medium traversed by the rays. According to Compton's theory,[1] in each individual stage of the scattering process half of the original energy quantum $h\nu$ of the primary radiation (frequency ν) is passed on to the liberated electron; the latter is emitted in almost the same direction as the primary ray. The other half of the energy goes on as an energy quantum of frequency $\nu/2$. The tertiary radiation has accordingly the frequency $\nu/4$, and so on. In addition to the original radiation of greatest penetrating power (highest frequency), there must therefore also exist at any given height secondary, tertiary, etc., rays of smaller hardness, together with the electrons liberated by them; these latter, however, would have much greater range and velocity than the fastest β-rays of radioactive substances.

The hardest component of the ultra-gamma radiation would possess an absorption coefficient (in water) of $1 \cdot 8 \cdot 10^{-3}$ cm.$^{-1}$, according to Millikan and Cameron, or of $0 \cdot 9 \cdot 10^{-3}$ cm.$^{-1}$ according to Hoffmann. The proportion of soft radiation would be greater at greater altitudes, as follows from absorption measurements made with lead screens on mountains.[2]

If it is assumed—as is indeed most likely—that the ultra-gamma radiation is a periodic radiation of higher frequency than ordinary γ-rays, it is possible to calculate the wavelength of the radiation from a formula developed by Compton (*loc. cit.*) for Röntgen rays, and verified for γ-rays by N. Ahmad.[3]

In this formula the so-called mass absorption coefficient (the quotient of the absorption coefficient and the density of the absorbing medium) is expressed as the sum of two quantities: the "scattering coefficient" and the "true

[1] *Phys. Rev.* (2), **21**, 494 (1923).

[2] K. Büttner, *Zeitschr. f. Geophys.*, **2**, 291 (1926), No. 7.

[3] *Proc. Roy. Soc.*, A, **109**, 206 (1925).

absorption coefficient." The latter is quite negligible in comparison with the other in the case of matter of low atomic weight (air, water). Millikan (*loc. cit.*) calculates in this way for the two extreme experimental values $\mu/\rho = 1\cdot8$ and $3\cdot0 \cdot 10^{-3}$ cm.$^2/g$ the wavelengths of $3\cdot8$ and $6\cdot3 \cdot 10^{-12}$ cm. From Hoffmann's values for the hardest component of the ultra-gamma radiation a wavelength of $2 \cdot 10^{-12}$ cm. would result. Comparing with this the shortest known wavelength of the γ-rays of a radioactive substance—according to Thibaud,[1] $\lambda = 0\cdot00557$ Ångstrom, *i.e.*, 56.10^{-12} cm.—it is seen that the *höhenstrahlung* may well be called ultra-gamma radiation, since its wavelength is ten to thirty times smaller, and its frequency therefore that much greater, than that of the hardest γ-rays. Of course, the justification for the application of the above and similar formulæ [2] to the unknown spectral region of the *höhenstrahlung* is extremely doubtful, more especially as certain conditions are not fulfilled in the measurements of μ/ρ; the results given can, therefore, only be regarded as attempts to determine the order of magnitude of the wavelength. W. Kolhörster [3] obtained with Bothe's formula somewhat higher values.

The secondary electrons liberated by the ultra-gamma radiation ($\lambda = 3\cdot8 \cdot 10^{-12}$ cm.) have, according to Millikan, a range in air of more than 50 metres, corresponding to free passage through a potential difference of $1\cdot5 \cdot 10^7$ volts. For the still harder component of the ultra-gamma radiation found by Hoffmann ($\lambda = 2 \cdot 10^{-12}$ cm.) secondary electrons of 31,000,000 volts would result. Even electrons of this great velocity, however, would not be able to penetrate a layer of metal (*e.g.*, zinc) 1 cm. thick.

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[1] *Compt. Rend.*, **179**, 167 (1924); *Journ. d. Phys.*, **6**, 82 (1925).

[2] W. Bothe, *Zeitschr. f. Phys.*, **34**, 819 (1925); Dirac, *Proc. Roy. Soc.*, A, **111**, 405 (1926).

[3] *Zeitschr. f. Phys.*, **36**, 147 (1926).

(e) *Direction and Variation of the Ultra-Gamma Radiation.*—As regards the direction of this radiation, Gockel (*loc. cit.*, p. 130) concluded from experiments in crevices of glaciers that this radiation falls approximately perpendicularly on the earth's surface. At the suggestion of Swann (see reference, p. 135), experiments were carried out by Miss J. Herrick as to the direction of this radiation, but the results of these cannot be regarded as decisive ; indications were, however, obtained that the radiation comes from above. At the instance of Gockel, following a suggestion of Nernst, Kolhörster,[1] with G. v. Salis, then undertook a series of measurements in the summers from 1923 to 1926 on a glacier near the Jungfrau Ridge, at a height of 3,550 metres. In all the tests a definite daily variation was shown whose amplitude amounted to about 15 per cent. of the total value of the *höhenstrahlung*. As the apparatus was gradually lowered into a slit in the ice the daily variation became smaller, until at 10 metres depth it completely disappeared. The maxima seem to coincide with the zenith position of the Milky Way and neighbouring regions of the heavens (Andromeda nebula, constellation of Hercules). The daily period shifts with the season of the year. Analogous results were obtained by K. Büttner (*loc. cit.*) in the summer of 1926, both at 3 to 4 km. height and, with complete protection from earth radiation, at sea level.

In opposition to this, Millikan and his collaborators,[2] at 4,000 metres above sea level, found no diminution in the radiation when the Milky Way was screened by a mountain ; from this they concluded that the *höhenstrahlung* comes equally in all directions from cosmic space. L. Myssowski and L. Tuwim [3] and more recently E. Steinke (1927) came to similar conclusions.

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[1] *Sitz.-Ber. Preuss. Akad. d. W.*, **34,** 366 (1923) ; **36,** 120 (1925).
[2] *Phys. Rev.* (2), **28,** 851 (1926) ; *Ann. d. Phys.* (4), **79,** 572 (1926).
[3] *Zeitschr. f. Phys.*, **35,** 299 (1925) ; **36,** 615 (1926).

In places at moderate altitudes the older observations of the *höhenstrahlung*, of course, hardly yield definite indications of regular variations, since the absolute value of this component is then too small. Most authors report that there is no difference in the radiation by day and night. This was also established by balloon ascents (V. F. Hess). The accurate records of ultra-gamma radiation in Königsberg by Hoffmann exhibit only small, irregular variations in the radiation, spreading usually over several hours and lying between about 0·86 and 1·09 I. The irregular variations were ascribed by Myssowski and Tuwim [1] to changes in the absorption of the cosmic radiation caused by alterations of atmospheric pressure.

According to Bauer and Swann,[2] the long series of sea observations of the Carnegie Expeditions shows irregular variations between 3·1 and 4·5 I in the value of *höhenstrahlung*, plus residual radiation. Similar results are reported by Simpson and Wright [3] and McLennan and McLeod [4] for shorter series of experiments.

According to Swann,[5] during a total eclipse of the sun the variations in the radiation at New Haven were greater than on the control days. In general, observations during the solar eclipses of 1912, 1914 and 1918 [6] have shown that the average value of the penetrating radiation is not altered during the period of eclipse.

It is therefore clearly proved that the ultra-gamma radiation cannot come directly and in straight lines from the sun.

[1] *Zeitschr. f. Phys.*, **39**, 146 (1926).

[2] Research Department of Terrestrial Magnetism, Carnegie Institution of Washington, III., No. 175 (1918).

[3] *Proc. Roy. Soc.*, A, **85**, 175 (1911).

[4] *Phil. Mag.* (6), **26**, 740 (1913).

[5] *Phys. Rev.* (2), **25**, 901 (1925).

[6] de Broglie, *Compt. Rend.*, **154**, 1654 (1912); Palazzo, *Mem. Soc. Spettr. Ital.*, VIII. (1919); Kolhörster, *Die Naturwiss.*, **7**, 412 (1919); Bauer, Fisk, Mauchly, *Terr. Magn.*, **24**, 87 (1919).

During the passage of Halley's Comet through the earth's orbit indications were obtained in some places of a rise in the penetrating radiation. Wigand [1] assumed that strongly-ionising matter must then have entered into the uppermost layers of the atmosphere.

(*f*) *Hypotheses on the Origin of the Ultra-Gamma Radiation.*—In the year 1906, long before the discovery of the ultra-gamma radiation itself, Richardson [2] suggested that the penetrating radiation must be of extraterrestrial origin and, further, that it must come from the sun. This hypothesis was untenable, since calculations showed that the rays from the radioactive substances in the earth sufficed to account for the variations in the total radiation, and that a radiation of the nature of the ordinary γ-rays could not penetrate the earth's atmosphere without developing in the middle and upper layers of the air an ionisation a hundred times greater than that corresponding to the conductivities actually observed.

Balloon observations then led Hess [3] to the assumption of a new source of radiation, whose rays enter the atmosphere from above. This radiation cannot come directly from the sun, *i.e.*, in straight lines, since the balloon observations showed no difference in the radiation by day and by night ; quantitative considerations further showed that the known radioactive substances in the air are quite insufficient to bring about the observed effect, and that the penetrating power of these cosmic rays must be much greater than that of the ordinary γ-rays.

A theoretical investigation by Schweidler [4] on the possible causes of the ultra-gamma radiation shows that the planets, the sun, the moon, and the other heavenly bodies cannot be considered as the source of the radiation unless quite extraordinary values of radioactivity are

[1] *Phys. Zeitschr.*, **18,** 1 (1917).

[2] *Nature,* **73,** 583 (1906) ; **74,** 55 (1906).

[3] *Wien. Ber.*, **121,** 2001 (1912) ; **122,** 1053 (1913).

[4] *Elster-Geitel-Festschr.*, Brunswick, 1915.

ascribed to them. The easiest assumption which can be made from the observations is that in space there exists evenly-distributed cosmic material in an extremely fine state of division ; the radioactivity of this matter need only be about 100 times greater than that of the primary rocks, like granite. The possibility of the existence in the upper layers of the atmosphere of a hitherto unknown radioactive gas was suggested by Schweidler, but the observed curve, showing the increase of the radiation with the height, could not be explained on this assumption.

Following out the idea of Bongards as to the entering of radioactive recoil atoms from the sun into the earth's atmosphere, Swinne [1] maintains that such radioactive atoms of solar origin must penetrate into the auroral zone, and he regards it as possible that the cosmic dust deposited on polar snowfields may be strongly radioactive. Experiment shows that this is not the case. It must also be remembered that the ultra-gamma radiation cannot be attributed to any known radioactive element, since the absorption coefficient is at least ten times smaller than that of the hardest known γ-radiation.

Kolhörster [2] points out that in 1914 Wigand had suggested the idea that the cause of the ultra-gamma radiation was to be sought in finely-divided active cosmic dust collected at the lower limit of the stratosphere, at about 11 km. and upwards, by the action of the temperature inversion existing there. Linke [3] independently developed similar considerations. On the assumption that this radiating matter is distributed at heights from 10 to 80 km., with its centre of gravity at about 20 km., the relation between the height and the intensity of the radiation as calculated is in very good agreement with the curve obtained experimentally, as is also the absorption

[1] *Die Naturwiss.*, **7**, 412 (1919).

[2] *Das Weltall*, **14**, 97, 114 (1914).

[3] *Meteorol. Zeitschr.*, **33**, 157 (1916).

coefficient. Linke [1] has been able for the most part to answer the objections of Bergwitz [2] to his theory.

The problem of the ultra-gamma radiation has been dealt with in a particularly thorough manner by R. Seeliger. [3] As it is not known how much of the ionisation produced by the *höhenstrahlung* is due to actual volume ionisation of the gas and how much to the action of secondary radiation from the walls, he makes the most varied assumptions as to this, and then calculates the height-intensity curves of the radiation. The curves so obtained, however, all follow approximately the same course. Seeliger then examined theoretically the case where the radiating matter is evenly distributed to given heights. These calculations are generalisations of the investigations of Schweidler and Linke, and give absorption coefficients which agree well with the observed value. Calculation of the specific radioactivity per unit volume again leads, as with Linke, to most improbably high values (the equivalent of 10^{-8} gm. radium per cubic centimetre).

Another " terrestrial " hypothesis is the following. One might consider the *höhenstrahlung* as a kind of β-radiation of extremely high velocity (almost that of light), and that such extreme cathode rays are produced in the strong electric fields of thunder clouds (C. T. R. Wilson [4]) ; the rays can then manifest themselves either directly or by the production of secondary radiation. Serious consideration and also direct experiment [5] are both against this " terrestrial " hypothesis.

When the possibility of the direct solar origin of the *höhenstrahlung* had been excluded by the results of measurements during eclipses, etc., the further possibility was considered that the radiation might originate in-

[1] *Meteorol. Zeitschr.*, **33**, 510 (1916).

[2] *Meteorol. Zeitschr.*, **33**, 310 (1916).

[3] *Münch. Sitz.-Ber.*, 1918, No. 1, and *Die Naturwiss.*, **6**, 89 (1918).

[4] *Proc. Phys. Soc.*, **37**, 32 (1925) ; *Cambr. Proc.*, **22**, 534 (1925).

[5] Millikan and Cameron, *Phys. Rev.* (2), **28**, 856 (1926).

directly from the sun. Schweidler [1] suggests that the corpuscular radiation emitted from the sun (of the nature of α- and β-rays) may be able to produce the *höhenstrahlung* as a kind of secondary radiation. Similar ideas have been put forward by St. Meyer,[2] Kolhörster,[3] and Swinne.[4] The electrons emitted by the white-hot sun would naturally be dragged in a spiral path round the magnetic pole of the earth, and therefore no direct influence during eclipses or at night would be noticed. According to Birkeland, these cathode rays from the sun would have energies corresponding to a potential difference of $8 . 10^8$ volts, and the secondary γ-rays caused by them would accordingly have a wavelength of only 10^{-13} cm., which is far less than the wavelengths of the known γ-rays of radioactive elements. According to Swinne, an increase of the ultragamma radiation should also be expected in the aurora zone. Experimental investigations on this point have been planned by Vegard and by Swann. Swann [5] considers that solar electrons, whose velocities approach that of light, produce hardly any direct ionisation. The *höhenstrahlung* might be a secondary radiation effect produced by these electrons. Schweidler [6] has latterly been disposed to regard the *höhenstrahlung* as a secondary effect, not of electrons, but of positive rays (hydrogen nuclei) which are emitted from the sun. Parallel observations by A. Nodon [7] of the penetrating radiation in its relation to earth magnetism, earth currents, and sunspots seem in general to point to a connection between the intensity of the *höhenstrahlung* and the sun's activity. M. Akiyama [8]

[1] *Elster-Geitel-Festschr.*, Brunswick, 1915, p. 411.

[2] *Cf.* Hess, *Vortr. d. Ver. z. Verbr. naturw. Kenntnisse, Wien,* **59** No. 2 (1919).

[3] *Die Naturwiss.*, **7**, 412 (1919).

[4] *Die Naturwiss.*, **7**, 529 (1919).

[5] *Journ. Franklin Inst.*, November, 1919, p. 577.

[6] *Terr. Mag.*, **27**, 105 (1922).

[7] *Compt. Rend.*, **173**, 722 (1921).

[8] *Japanese Journ. of Astr. and Geophys.*, **3**, No. 1, 1925.

also comes to quite similar conclusions ; he points out the similarity between the daily and yearly frequency distribution of the aurora borealis and the daily and yearly period of the penetrating radiation observed in some places.

The fact that quite recently γ-ray components of a penetrating power almost equal to that of the *höhenstrahlung* have been found to be emitted by radioactive substances has led some authors to suppose that the *höhenstrahlung* may arise from known radioactive substances (R. A. Millikan and R. M. Otis,[1] G. Hoffmann,[2] F. Behounek [3]). The presence of such substances in the higher layers of the atmosphere could, however, only be explained on the basis of the hypothesis of Bongards, of the wandering of radioactive atoms from the sun to the earth. This, again, leads to many contradictions. Meanwhile, both Millikan and Hoffmann have abandoned this point of view, and it can be said that by the more recent researches mentioned above (§ 23 (6), (*d*) and (*e*)) the existence of a cosmic "ultra-gamma radiation" is proved.

A totally different hypothesis of the origin of the ultragamma radiation has been put forward by Nernst.[4] He assumes that " atoms of chemical elements of high atomic number are formed in the cosmos by incidental changes in the energy content of the luminiferous ether, just as conversely it must be assumed that, in continuation of the so-called radioactive decomposition, the atoms of helium and hydrogen are again converted into the *nullpunktsenergie* of the ether." According to Nernst, these new elements, of high atomic weight, would first form the large, cold nebula stars. These would pass gradually into

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[1] *Phys. Rev.*, **23**, 778 (1924) ; R. A. Millikan, *Nature*, **114**, 141 (1924).

[2] *Phys. Zeitschr.*, **26**, 40, 669 (1925) ; **27**, 291 (1926).

[3] *Phys. Zeitschr.*, **27**, 8, 536 (1926).

[4] " Das Weltgebaüde im Lichte der neueren Forschung (Berlin : Springer, 1921).

the young red giant stars, whose radiation is essentially a temperature radiation. From these are then formed later the small white dwarf stars (suns), etc. Radio-elements of high atomic number, with extremely penetrating radiation of high frequency, would therefore be expected to be found chiefly in the Milky Way, in those places where young giant stars have formed or are in course of formation. As has already been pointed out, Kolhörster's observations on the Jungfrau Ridge make this hypothesis very likely. Deslandres [1] has put forward, quite independently of Nernst, the view that the yellow giant stars may be the source of the penetrating *höhenstrahlung.* He calls this radiation " ultra-Röntgen radiation " instead of " ultra-gamma radiation."

Millikan estimates the wavelength range of the *höhenstrahlung* from his absorption experiments *(loc. cit.)* as $3 \cdot 8$ to $6 \cdot 3 \cdot 10^{-12}$ cm. Calculation from the known energy values of the frequency and wavelength of the radiation accompanying the formation of a helium atom from hydrogen nuclei, or the absorption of an electron in the nucleus, yield figures of the same order of magnitude. Millikan therefore regards it as probable that processes of this kind, which may very probably be proceeding continuously in many spots in the universe, are the actual cause of the ultra-gamma radiation *(cf.* also A. L. Hughes and J. E. M. Jauncey [2]).

It is possible to imagine also atomic processes of other kinds in which radiation of short wavelength is produced, such as the transformation of matter into radiation,[3] or, finally, the formation of " neutrons " (combination of a proton with an electron [4]). The last-named transforma-

[1] *Nature,* **110,** 847 (1922).

[2] *Proc. Nat. Acad. of Sc., Washington,* **12,** 169 ; *Nature,* **117,** 193 (1926).

[3] J. H. Jeans, *Nature,* **117,** 18 (1926).

[4] A. v. Antropoff, *Naturwiss.,* **14,** 493 (1926 ; G. Condon, *Phys. Rev.* (2), **27,** 644 (1926) ; Jeans, *loc. cit.* ; Eddington, *Nature,* **117,** 26 (1926).

tion would produce radiation of a much shorter wave-length (10^{-13} cm.) than that of the ultra-gamma radiation, and therefore the first mentioned possibility (formation of helium from hydrogen nuclei) or some similar transformation in the atomic nucleus of one of the many elements which occur in the universe is the most probable source of the ultra-gamma radiation. The increase in radiation first found in the Bernese Alps by Kolhörster during the zenith period of certain regions of the heavens, as well as the daily maximum by sidereal time, even at sea level, suggests that the Milky Way, the constellation of Hercules, and the Andromeda nebula are regions where, quite in the sense of Nernst's original hypothesis, such atomic processes are occurring.

There nevertheless always remains, as mentioned above, the possibility that the *höhenstrahlung* is a secondary radiation excited by primary corpuscular rays (a-rays, β-rays, or electrons of almost light velocity) shot into the atmosphere by the sun. Unfortunately, experiments which might enable us to decide between the hypotheses (measurements of the *höhenstrahlung* in the region of the auroral zone) are entirely lacking.

(*g*) *Comparison of the Ionisation due to the Ultra-Gamma Radiation with that of the other three Components in closed Vessels.*—At sea level the ionisation due to the *höhenstrahlung* in vessels filled with air at normal pressure amounts, as we have seen, to 1 to 2 I. It is of interest to compare this value with the approximate value due to the residual radiation, the earth radiation and the atmospheric radiation (*cf.* § 23 (3)). The extreme and mean values of these components at sea level, in carefully-purified vessels, are :

$$q_0 = 0{\cdot}4 \text{ to } \quad 6 \text{ I (mean, 4 I)}$$
$$q_E = 2 \quad \text{,, } 14 \text{ I (mean, 3 I)}$$
$$q_A = 0 \quad \text{,, } \quad 0{\cdot}8 \text{ I (mean, 0·2 I)}$$
$$q_H = 0{\cdot}6 \text{ ,, } \quad 2 \text{ I (mean, 1·5 I).}$$

§ 24. Soil Respiration.

In speaking of the equilibrium of emanation in the atmosphere mention has already been made of the important part played by the emergence of strongly-ionised soil gases, rich in emanation, into the free atmosphere. This process is called (following a suggestion of A. Daunderer) " soil respiration." H. Ebert [1] was the first to point out that the soil respiration is also of great significance for the ionic content and free space charge of the lowest layers of the atmosphere. When falling atmospheric pressure, the action of sunlight, or the suction of the wind cause strongly-ionised soil gases to be drawn from the capillaries of the earth into the free air, not only is the ion number in the lowest layers of the air momentarily increased, but ion adsorption phenomena also occur at the walls of the fine pores of the soil. Since it follows from experiments of J. Zeleny,[2] Villari and Simpson [3] that the negative ions are more readily adsorbed in such transpiration processes than the positive, the soil gases finally emerging into the free air will contain an excess of positive ions, and therefore a free positive space charge.

Ebert has attempted to explain by this process the maintenance of the negative charge on the earth and of the positive space charge in the atmosphere ; in short, the permanent electric field between earth and air. According to his reasoning, the vertical conductivity current, which is continuously flowing to the earth, is balanced by the continual upward convection of positive space charge due to the respiration of the soil.

Ebert [4] was able for the most part to answer the original

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[1] *Phys. Zeitschr.*, **5,** 135, 499 (1904).

[2] *Phil. Mag.* (5), **46,** 120 (1898) ; *Phys. Zeitschr.*, **4,** 667 (1903).

[3] *Phys. Zeitschr.*, **4,** 480 ; *Phil. Mag.* (6), **6,** 589 (1903).

[4] *Phys. Zeitschr.*, **6,** 825, 828 (1905) ; *Jahrb. f. Rad. u. Elektr.*, **3,** 61 (1905).

objections of Simpson [1] and of H. Gerdien.[2]   In particular, he was able, with K. Kurz,[3] to show by records of the electrical dissipation immediately above the earth that the suggested process (emergence of an excess of positive ions from the ground) does actually occur in nature.

The apparatus of Ebert and Kurz is shown schematically in Fig. 13.   A metal plate of 600 sq. cm. surface (P) is hung in a vertical position on an insulating hook, J, of Gockel's pattern, immediately above the ground.   The whole arrangement is electrostatically shielded by the
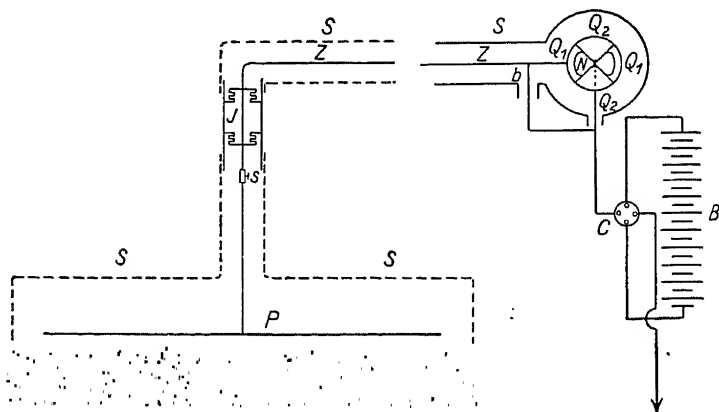
Fig. 13.—Apparatus of Ebert and Kurz for recording the amount of ions emitted from the soil.

earthed net S.   The plate P, connected to a recording electrometer, is automatically connected for a moment every hour with a battery and charged to 120 volts.   The loss of charge during the whole of the following hour is then registered by a quadrant electrometer.   Within the space enclosed by the net the current is practically at saturation value.   It was found that the ionisation produced in the space amounted at Munich to 100 I during the

[1] *Phys. Zeitschr.*, **5**, 325, 734 (1904).
[2] *Phys. Zeitschr.*, **6**, 647 (1905).
[3] *Abh. d. Bayer. Akad. d. Wiss.*, **35**, No. 2, 1909 ; *Phys. Zeitschr.*, **11**, 389 (1910).

summer months, and 150 I in the winter months, *i.e.*, the air directly above the ground is two or three times less strongly ionised than the air within the soil (*cf.* p. 84).

Direct proof of the occurrence of soil respiration was then given by working two similar arrangements of this sort simultaneously, one or other of which in turn was entirely screened from the earth surface by means of a metal plate.   The records showed that about 7·9 electrostatic units more electricity per square metre per hour flowed in the form of free ions from the side exposed to the soil respiration than from the covered side. From this it may be concluded that 60 per cent. of the ions present near the earth is introduced into the air by the action of soil respiration ; they may either be already formed in the soil gases or may be subsequently produced by the radioactive constituents of the gases.   On the average a distinct preponderance of positive ions is to be noted.

Ebert and Kurz were also able to show that the excess positive charge was larger when the ground was covered with a layer of fine, inactive quartz sand 2 cm. thick. The positive space charge is therefore the larger the finer the capillaries of the soil (" diaphragm effect "). Experiment also shows that only the first few centimetres thickness of the soil take part in the respiration effect. The excess of positive electricity emitted from the earth amounted, when the ground was not sanded, to 1·04 E.S.U.   As in Munich 10·8 E.S.U. of positive electricity, on the average, is carried to the earth by the normal vertical conductivity current (2.10^{-16} amps. per square centimetre), it is evident from the experiments of Ebert and Kurz themselves that the soil respiration is not nearly sufficient to compensate for the downward directed conduction current, at least on sandy soils, under the conditions of the experiments.   But even if it is assumed, with Ebert and Kurz, that actually, *i.e.*, in nature, the

positive charges emitted by soil respiration are considerably greater, Simpson's objection still remains to be answered : the soil respiration is only acting over land, and there only on dry surfaces containing humus or vegetation, while the normal conduction current continuously flows to earth everywhere, even over the sea. Further serious objections have been raised by W. F. G. Swann, R. Seeliger and E. Schweidler, pertaining to the distribution of space charges by vertical and horizontal air currents. It has been conclusively proved that the soil respiration as measured by Ebert is in any case quantitatively insufficient to explain the production and maintenance of the earth's field.[1]

None the less, observations of the ionisation in the layers of air near the ground are of permanent value for atmospheric electrical investigation. After the records of Ebert and Kurz, mentioned above, more lengthy observations were carried out at Freiburg (Switzerland) by A. Gockel [2] and J. Olujic [3] with a simplified apparatus, more nearly corresponding with natural conditions, designed by the former author. Over freshly-dug plough land the ionisation is about twice as great as on turf ; on hard sandstone rock it is still less, and quite negligible on very wet ground. In Freiburg also the amounts of emerging positive ions outweighed, on the average, the negative. On wet soils, where the soil respiration is practically zero, equal amounts of positive and negative ions were found.

[1] E. Schweidler, *Ann. d. Phys.*, **63**, 726 (1920).

[2] *Neue Denkschr. Schweizer Naturf. Ges.*, **53**, 1 Abh., 1917.

[3] *Diss. Freiburg* (Switzerland), 1918 (printed by Aug. Priess, Leipzig), p. 51.

CHAPTER IV

PROCESSES WHICH RESULT IN THE DESTRUCTION OF IONS

AMONG the processes to be included under this head in the wider sense we have already, in § 3, distinguished two groups :

1. Removal of ions—
    (a) By diffusion and adsorption ; and
    (b) By the action of electric fields.
2. Actual destruction of ions—
    (a) By recombination with ions of opposite sign, and
    (b) By agglomeration on larger uncharged particles ("fixation").

We will now turn to the discussion of all these processes, in so far as they are essential for the understanding of the electrical equilibrium of the atmosphere.

§ 25. Adsorption and Diffusion of Ions.

The diffusion of ions can naturally only play a part in places where the ionic content is not constant, *i.e.*, where an ionic concentration gradient exists. In the atmosphere this is pre-eminently the case at the boundary layer between the strongly-ionised soil gases and the relatively weakly-ionised free air. Diffusion, however, also acts indirectly as an ion-removing process, in conjunction with adsorption, at those places where free air comes in contact with solid or liquid surfaces (water surfaces, rock, vegetation and the like). Adsorption causes a steady passage of ions of both signs from the layers of gas next to the boundary surface into the solid or liquid surface, where they then give up their charge. This may be regarded as

simple electrostatic attraction.   H. Ebert [1] calculated the magnitude of this attractive force, and arrived at the result that an ion 1 mm. from the wall would require two hours to reach the wall, while an ion 0·001 mm. from the wall would reach it in 10^{-5} seconds.   The adsorption effect is thus practically only active in a layer of gas 0·01 mm. thick immediately adjacent to a solid or liquid surface. This layer is therefore always almost free from ions, and, on account of the rapid fall of ion concentration, ions can continually pass into it from the bulk of the gas.   If the ionising agent were suddenly to become inactive, the gas would gradually lose its ions, even if no ordinary recombination took place.

E. Riecke [2] has developed a theory of ion adsorption at the surface of the earth : the number of ions disappearing by adsorption at the earth's surface per square centimetre per second is proportional to the ionic content, the mean molecular velocity of the ions (in the sense of the kinetic theory), and a coefficient (adsorption coefficient) depending on the nature of the ions in question and their charge. The negative ion, for instance, diffuses faster than the positive ion.   This effect is also noticeable in the streaming of strongly-ionised soil gases through the capillary pores of the soil (*cf.* Ebert, *loc. cit.*).

Finally, the deposition of ions on solid or liquid particles in the atmosphere (this process has been described as " fixation " at the beginning of the present chapter) must be considered as an adsorption process in the wider sense.

This process and the adsorption of ions in the capillaries of the soil are of the greatest importance for the electrical equilibrium of the atmosphere.   The latter is particularly significant, since an excess of positive space charge thereby passes into the free atmosphere (*cf.* § 24, Soil Respiration).

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[1] *Jahrb. f. Rad. u. Elektr.*, **3,** 61 (1906).
[2] *Göttinger Nachr.*, 1903, p. 83 ; *Ann. d. Phys.*, **12,** 80 (1903).

§ 26. Ion Destruction by Recombination.

As has already been remarked in § 3, by far the most important of all ion-destroying processes is that of recombination.   We will first discuss the method of determining the recombination coefficient a, as far as it comes into consideration in connection with atmospheric electricity, starting from the simplest case, where only small ions exist in the gas.   We will then proceed to the more general case, which is applicable to the conditions actually existing in the atmosphere (taking into account recombination of small and large ions and the adsorption of ions on condensation nuclei, etc.).

The necessary requirement for the applicability of the simple relation (*cf.* § 3)

$$\frac{dn}{dt} = q - a \cdot n^2$$

is that the conditions of the experiment shall always be so chosen that diffusion and adsorption can be neglected. An artificial source of ionisation (radioactive preparation, X-ray tube) is set up so that the ionisation produced by it is very much greater than the natural ionisation of the air ; the latter may then be neglected.   In the direct methods for determining a the essential feature is the measurement of the rate of decrease or increase in the ion number (n) after cutting off or introducing the source of ionisation.   The only factors affecting the ion number are the action of the ioniser and the process of recombination ; at the end of the chosen time of the measurement all the ions present are deposited almost instantaneously on an electrode by the application of a strong electric field.

There are also other indirect methods, in which a current flowing through the gas acts in conjunction with the recombination effect to cause a decrease in the ionic content.   If the ionic mobility is known, the recombina-

tion coefficient a may then be calculated from the relation between the current and the field strength.[1]

For determinations of a in free air the aspiration method of Rutherford, first applied by A. Schuster,[2] has proved particularly suitable. A cylindrical condenser connected to an electrometer (as in Ebert's or Gerdien's aspiration apparatus) is provided with an additional tube in which the air is first ionised by a preparation emitting a-rays at a determined position at distance L cm. from the measuring condenser. Alteration of the distance L alters the time available for the recombination of the ions drawn along in the air stream before they reach the field of the measuring condenser. Since in principle it is immaterial whether the source of ionisation is cut off at a given time, or whether the ions produced are removed from their place of origin by a stream of air, this corresponds to the special case $t = 0$, $q = 0$. The ion number per cubic centimetre, which has the value n_o at the place of origin, will be the greater in the measuring condenser the less the distance travelled by the ions from their place of origin. Let t be the time in which the air stream passes from the source of ionisation to the measuring condenser. Then, by integration of the equation $\dfrac{dn}{dt} = a \cdot n^2$, it follows that the ion number observed in the condenser is

$$n = \frac{n_o}{1 + an_o \cdot t}$$

From this equation a may be calculated. Since, however, the value of n_o, the ion number at the spot where the active preparation is placed, is usually unknown, the preparation is next placed at another distance, L', from

[1] Compare, *e.g.*, Thomson, " Conduction of Electricity through Gases " (Cambridge, 1906); also the reviews of Harms, *Jahrb. f. Rad. u. Elektr.*, **3**, 321 (1900), and R. Seeliger, " Die Ionisation der Gase," in L. Graetz, *Handb. d. Elektr. u. d. Magn.*, **3**, 372 *et seq.* (1923).

[2] *Manchester Soc. Mem.*, **48**, Vol. XII., 190.

the measuring condenser (by means of a second tube attachment of different length) and the new ion number (n') in the condenser determined. If $L' > L$, n' will be smaller than n.

From the two equations

$$\frac{1}{n} = \frac{1}{n_0} + a\frac{L}{G}, \quad \frac{1}{n'} = \frac{1}{n_0} + a\frac{L'}{G}$$

the unknown n_0 may then easily be eliminated. The quotients $\dfrac{L}{G}$ and $\dfrac{L'}{G}$ (where G is the velocity of the air in the tube) correspond to the times taken by the ion cloud in the first and second experiments to pass from their place of origin to the measuring condenser. It therefore follows that

$$\frac{a}{G} \cdot (L - L') = \frac{1}{n} - \frac{1}{n'}.$$

Now, not n and n', but the charges corresponding to them, $Q = e \cdot n$ and $Q' = e \cdot n'$, are directly measured, and therefore the experiments yield the values, not of a, but of $\dfrac{a}{e}$, as in the following equation :

$$\frac{a}{e} \cdot \frac{L - L'}{G} = \frac{1}{Q} - \frac{1}{Q'}.$$

That is to say, the numerical value of a is dependent on the magnitude of the elementary charge. The numerical values given in the following pages are based on Millikan's value, $e = 4\cdot77 \cdot 10^{-10}$ E.S.U.

A. Schuster (*loc. cit.*) obtained by this method values of a for free air in and near Manchester of 3 to $4\cdot6 \cdot 10^{-6}$ cm.^{3}/ sec., and for carefully-dried dust-free air $1\cdot55 \cdot 10^{-6}$. H. Mache and T. Rimmer,[1] using the same method, obtained values in Vienna of $2\cdot95 \cdot 10^{-6}$ for open air and, $6\cdot45 \cdot 10^{-6}$ for the air of a cellar. Numerous measure-

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[1] *Phys. Zeitschr.*, **7**, 617 (1906).

ments have been made by K. W. F. Kohlrausch [1] and A. Gockel [2] at land stations in the Austrian Alpine regions and at various Swiss stations. Their results may be summarised by saying that Schuster's method gives the value $1 \cdot 6 \cdot 10^{-6}$ in dry, dust-free air, while in the open air, on account of the recombination which takes place between small and large ions, the values generally lie between 2 and 3.10^{-6}.

It appears that Schuster's method gives values much too small for the recombination coefficient, particularly where, as in free air, both small and large ions are present. Kohlrausch (*loc. cit.*) investigated thoroughly the sources of error in Schuster's method, and gave an improved formula which takes into account the fact that the air velocity in the tube increases from the outer parts of the tube to the middle (axis), in accordance with Poiseuille's law for non-turbulent flow. The effect of adsorption of ions on the walls of the tube must also be taken into account. It has, however, not been possible so far to arrive at a rigid theoretical treatment of Schuster's aspiration method, taking also into account the diffusion factor.

P. Langevin [3] has shown that the following proportionality exists between the recombination coefficient α and the sum of the two ionic mobilities (k_+ and k_-) :

$$\alpha = 4\pi e \cdot \eta \cdot 300(k_+ + k_-).$$

The numerical factor 300 enters when, as is usual, the mobilities are expressed in cm./sec. : volt/cm. The factor η denotes that fraction of the total number of collisions between positive and negative ions which results in recombination and neutralisation of the charges (" percentage of effective collisions "). In free air this factor

[1] *Wiener. Ber.*, **123**, 1929, 2321 (1914).

[2] *Neue Denkschr. Schweizer Naturf. Ges.*, **54**, No. 1, 1917.

[3] *Compt. Rend.*, **137**, 177 (1903).

is, according to Kohlrausch, 0·45, while in carefully purified dry air, according to Langevin, η is 0·27.

E. v. Schweidler [1] has brought forward considerations which make it clear that Schuster's method always gives incorrect (*i.e.*, too low) values for the recombination coefficients in free air. The following discrepancy in the calculation of the ionisation from the simple equation

$$q = a \cdot n^2$$

shows the error particularly clearly. If, for example, we write $n_+ = n_- = 700$, $a = 3.10^{-6}$, values representing very fairly the average conditions in free air, the necessary ionisation works out at $q = 1·5$ I. This, as has been already mentioned, is equal to the ionisation due to the a-radiation of the radium emanation (10^{-16} curies/c.cm.) in the atmosphere acting alone. The other ionising agents present over dry land produce at least five times the ionisation given by the above calculation. It is therefore very probable that the true value of the recombination coefficient is considerably higher than is assumed from measurements by Schuster's method.

This method accordingly gives values which correspond essentially to the recombination of small ions. Actually, however, it is necessary to take into account recombination between small and large ions, and also the agglomeration of small ions to adsorption nuclei, if a clear statement of the relations in the atmosphere is aimed at. This was first accomplished by Schweidler, who has worked out the theory and methods for determining the effect of recombination with heavy ions and agglomeration to uncharged nuclei. [2] Similar methods were later used independently by J. J. Nolan [3] in collaboration with J. Enright and with Boylan and de Sachy, [4] also by A. D. Power. [5]

[1] *Wien. Ber.*, **127**, 953 (1918).
[2] *Wien. Ber.*, **127**, 953 (1918); **128**, 947 (1919); **133**, 23 (1924).
[3] *Proc. Roy. Irish Acad.*, A, **36**, 93 (1923).
[4] *Proc. Roy. Irish. Acad.*, A, **37**, 1 (1925).
[5] *Journ. Franklin Inst.*, **96**, 327 (1923).

Starting from the most general considerations, Schweid-ler shows that, in spite of the complication introduced by the simultaneous occurrence of processes with different velocities—the agglomeration of small ions on uncharged nuclei and the recombination of small and large ions—both processes may be formally expressed, for the stationary state, in one additional term, $\gamma \cdot n \cdot N$, in an equation of the following form :

$$q - a \cdot n^2 - \gamma \cdot n \cdot N = 0,$$

where N is the sum of the numbers of the oppositely charged large ions and the uncharged nuclei. Putting in this equation $\gamma \cdot N = \beta$, the above expression may be written :

$$q = \left(a + \frac{\beta}{n}\right) \cdot n^2 = a' \cdot n^2,$$

i.e., instead of a, we obtain a larger recombination coefficient a', which itself depends upon n, N, and the recombination coefficient γ between large and small ions.

For the experimental determination of a' Schweidler made use of a method which had already been employed by Rutherford [1] and McClung [2] for the measurement of the ordinary recombination with artificial ionisation. An ionisation vessel free from radioactive impurities was freshly filled with air, and was allowed to stand until equilibrium had been reached between the large and small ions. About five minutes was sufficient for this, as was shown by calculation. Immediately afterwards a high potential was applied to the vessel for a short time, so that all the ions were instantaneously removed from the whole volume, V. The quantity of electricity Q reaching the electrode in this way was measured :

$$Q = n \cdot e \cdot V,$$

from which the maximum ion number n in the absence of a field was obtained. The second measurement is the

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[1] *Phil. Mag.* (5), **44**, 422 (1897).
[2] *Phil. Mag.* (6), **3**, 283 (1902).

determination of the saturation current in the vessel, which gives q directly. a' then follows from the relation already given, $q = a' . n^2$. Schweidler's experiments at Innsbruck gave for a' a mean value of 29.10^{-6}, a figure about ten times greater than the value obtained in free air by Schuster's method. This also explains the discrepancy mentioned on p. 161 in the calculation of the ionisation q from the ion number and the recombination coefficient. The high values of a' make it easy to understand why in air rich in nuclei an ionisation of 10 to 15 I may produce ion numbers less than 1,000 per cubic centimetre. Over the sea the ionisation sinks to one-fifth, or even one-tenth, of the value over dry land, and yet the ion number is no smaller than over land, so it may be expected that the recombination is considerably less on account of the smaller number of nuclei in the air. Experiments on this point by Schweidler's method are, unfortunately, still lacking.

It must, of course, not be forgotten that a' itself depends on the number of ions present at the time. For this reason Schweidler found it convenient to replace it by the quantity β' by the following transformation (*cf.* p. 162) :

$$q = a . n^2 + \beta . n = (a . n + \beta) . n = \beta' . n.$$

The quantity $\beta' = a . n + \beta$ thus introduced he calls the *diminution constant* ("*verschwindungs constante*"), in analogy with the constants of decay in radioactive transformations. Actually β' signifies that fraction of the existing light ions (n) which disappears in unit time through recombination between all kinds of ions, and agglomeration of small ions on nuclei.

One can thus speak of a *linear law of recombination* in air containing nuclei (as opposed to the ordinary square law), since the number of ions disappearing in unit time may with sufficient accuracy be taken as proportional to the number of ions present.

In an analogous manner the reciprocal value $\dfrac{1}{\beta'} = \theta$ may be described as the " average life of the small ions." The numerical values of β' are naturally about a thousand times higher than those of α'. Thus Schweidler found the following values for the diminution constant : at Seeham (Salzburg), on land, 16 to 19.10^{-3} sec.$^{-1}$; at Innsbruck, 22.10^{-3}. The average life of the small ions is, accordingly, 60 to 46 seconds.

A. D. Power (*loc. cit.*) has attempted to find on experimental principles what function, $f(n)$, of the ion number satisfies the equation

$$\frac{dn}{dt} = q - f(n)$$

most nearly for the natural ionisation of the air. He comes to the conclusion, with Schweidler, that a linear function $f(n) = \beta'n$ satisfies the observations, so that the ordinary square term an^2 may practically be neglected in comparison with $\beta'n$. For the determination of the diminution constant β', Power employs observations of the ion content of a closed vessel at various times after complete removal of the ions by a strong field. The mean value of β' thus obtained is $6 \cdot 1 \cdot 10^{-3}$ sec.$^{-1}$, considerably lower than Schweidler's value. Power found that removal of moisture and dust from the ionisation vessel caused no appreciable alteration of the diminution constant. This is not in agreement with later results of Schlenck (see below).

Schweidler [1] subsequently gave the theoretical basis of a further method for determining the diminution constant, and the experimental proof was carried out by W. Schlenck.[2] The change of current intensity with rising potential in a cylindrical ionisation vessel is followed, and the potential at which the current strength is half the

[1] *Wien. Ber.*, **133**, 23 (1924).
[2] *Wien. Ber.*, **133**, 29 (1924).

saturation current is then found graphically from the curve obtained. β' may then be directly calculated from this value and the mean ionic mobility. Schlenck obtained values at Innsbruck by this method between 28 and 83.10^{-3} sec.$^{-1}$. The lowest value corresponds to less than 10,000 Aitken nuclei per cubic centimetre (Föhn wind prevailing), the highest to a nucleus content of 20,000 to 30,000 (with fog). This result is apparently not in agreement with the results of Power, but it may be remarked that the ordinary dust content of the air and the number of nuclei do not run parallel. The average value of the diminution constant at Innsbruck (open air), according to Schlenck, is 70.10^{-3} sec.$^{-1}$ with an ion number of 660 and an ionisation of 47 I.

If n is the number of small ions, N the number of large ions, N_o the number of uncharged Aitken nuclei, η_1 the coefficient of recombination between small ions and nuclei, and η_2 that between small ions and large ions of opposite charge, the stationary state for the small ions is characterised by the following equation :

$$dn/dt = q - a \cdot n^2 - \eta_1 \cdot N_o \cdot n - \eta_2 \cdot N \cdot n = 0.$$

Nolan and his collaborators were able to determine η_1 and η_2 separately, obtaining the value $9 \cdot 1 \cdot 10^{-6}$ cm.^{3}/sec. for the latter, and for the former a somewhat smaller figure $(7 \cdot 6 \cdot 10^{-6})$. Both coefficients are thus almost ten times larger than the ordinary recombination coefficient between the small ions. On the other hand, the recombination between large ions of opposite sign is quite negligible (the coefficient characterising this process is of the order of 10^{-9} cm.^{3}/sec.). The above-mentioned differences in the numerical value of the diminution constant are easily explainable by the occurrence of local variations in the number of nuclei N_o and the number of large ions N. In Dublin, Nolan, Boylan and de Sachy found as the average of a nine months' series of experi-

ments the values $N = 10,000$, $n = 116$, from which follows an ionisation $q = 22.5$ I. On the Irish coast, on the other hand, the number of large ions falls to 1,000 per cubic centimetre, and that of the small ions rises to 700, corresponding to an ionisation of $q = 14.5$ I. This is in accordance with the conditions at most land stations, where the diminution constant falls to about 20.10^{-3} sec.$^{-1}$.

To sum up, we may therefore say that, on account of the presence of large ions and Aitken nuclei in the free air, the destruction of ions takes place much more quickly than would be the case if only small ions were present. In the equation given above, representing the stationary state, the second term an^2 is far outweighed by the third and fourth terms, representing the disappearance of small ions by agglomeration on uncharged nuclei and by recombination with large ions of opposite sign. For this reason the expression obtained by summing up the negative terms $(a\,n + \eta_1\,N_o + \eta_2\,N)n$ in the following way :

$$dn/dt = q - \beta'.\,n = 0,$$

which is Schweidler's linear recombination law, is in accordance with experiment.

CHAPTER V

§ 27. Quantitative Treatment of the Simultaneous Formation and Destruction of Ions.

In the foregoing chapters we have discussed fully all the processes which contribute to the formation and destruction of ions. We will now pass to the question of how far the ionisers known to us are quantitatively sufficient to bring about the amount of ionisation actually observed in the atmosphere. We will carry out this ionisation balance for three cases :

(1) For the layers of air near the earth over dry land ;

(2) For the lower layers over the sea ; and

(3) For the free atmosphere up to the neighbourhood of the upper limits of the troposphere (9 km.).

1. Ionisation Balance over Dry Land.—We already know that ionising agencies of non-radioactive origin (photo-electric effect, Lenard effect, etc.) only come into consideration in exceptional cases, and we can therefore confine ourselves to the radioactive ionisers in the ground and in the air, together with the cosmic ultra-gamma rays. We will calculate the ionisation at about 1 metre height above the ground—at the height, that is to say, at which most apparatus for observations of atmospheric electricity are installed.

Calculations of this kind have been made by K. Kurz,[1] A. S. Eve,[2] J. Satterly,[3] V. F. Hess,[4] K. W. F. Kohl-

[1] *Habilit.-Schr. Techn. Hochsch.*, Munich, 1909 ; *Phys. Zeitschr.*, **10,** 834 (1909).

[2] *Phil. Mag.* (6), **21,** 26 (1911).

[3] *Phil. Mag.* (6), **20,** 23 (1910).

[4] *Wien. Ber.*, **119,** 145 (1910).

rausch,[1] E. Schweidler and Kohlrausch,[2] and by G. C. Simpson ; [3] newer observations now available make it necessary to effect a partial revision of these results.

We will first consider the ionising effect of the radioactive substances in the air itself ; the total ionisation, q_1, due to this cause, is made up of the combined effects of the α-, β- and γ-rays :

$$q_1 = q_1^{(\alpha)} + q_1^{(\beta)} + q_1^{(\gamma)}.$$

Since 1 gm. of radium emits $3 \cdot 72 \cdot 10^{10}$ α-particles per second,[4] and each α-particle of radium emanation, radium A, and radium C produces $1 \cdot 69 \cdot 10^5$, $1 \cdot 84 \cdot 10^5$ and $2 \cdot 37 \cdot 10^5$ pairs of ions respectively,[5] the ionisation due to the radium emanation in 1 c.c. of air (mean, 130.10^{-18} curies), with its decomposition products, will be

$$130.10^{-18} \cdot 3 \cdot 72.10^{10} \ (1 \cdot 69 + 1 \cdot 84 + 2 \cdot 37) \cdot 10^5 = 2 \cdot 85 \ I.$$

If, following Eve, the effect of thorium products is estimated at 60 per cent. of the ionisation produced by the radium products, *i.e.*, at $1 \cdot 7$ I, we obtain, neglecting the small effect of the actinium products :

$$q_1^{(\alpha)} = 4 \cdot 6 \ I.$$

Calculation of the ionisation produced by the β- and γ-radiation of the radioactive substances in the air gives, according to A. S. Eve, using the latest data,

$$q_1^{(\beta)} = 0 \cdot 2 \ I, \quad q_1^{(\gamma)} = 0 \cdot 15 \ I.$$

The total radiation from the radioactive substances in the air near the earth thus gives rise to an ionisation of

$$q_1 = 4 \cdot 6 + 0 \cdot 2 + 0 \cdot 15 = \text{about } 4 \cdot 9 \ I.$$

[1] *Phys. Zeitschr.*, **13,** 1193 (1912). ·

[2] Article " Atmosph. Elektrizität," in L. Graetz's *Handb. d. El. u. d. Magn.*, III., pp. 232, 270 (1915).

[3] *Monthly Weather Rev.*, **44,** 115 (1916).

[4] V. F. Hess and R. W. Lawson, *Wien. Ber.*, **127,** 405 (1918).

[5] St. Meyer and E. v. Schweidler, " Radioaktivität," p. 490, Leipzig, 1916.

We may now calculate the ionisation effect due to the radioactive substances in the earth (q_2). The α-radiation need not in this case be considered, since at 1 metre above the ground it is no longer directly acting, while, in any case, over ground covered with vegetation (a large portion of the earth's surface) it is vanishingly small, on account of the absorption of the rays.

Taking the average radium content of the ground as 2.10^{-12} gm. per cubic centimetre (*cf.* § 16), and bringing into consideration the β-rays of uranium X_1, uranium X_2, radium, radium D, and radium E—which, however, contribute only to a small extent on account of their small penetrating power—the total ionisation by β-radiation from the earth comes to

$$q_2^{(\beta)} = 0{\cdot}1 \text{ I.}$$

The β-radiation from the radioactive surface deposit formed from the decomposition products of emanation under the action of the earth's field may, as Schweidler has shown, be entirely neglected.

The γ-radiation from the radioactive substances in the earth amounts in all to

$$q_2^{(\gamma)} = 2{\cdot}0 \text{ I,}$$

assuming, with A. S. Eve, that the effect of the γ-rays of uranium X_2 and thorium D is as great as that of the γ-rays of radium C. Observation of the ionisation in closed vessels (*cf.* § 23 (5)) gives as the share of the earth radiation in zinc vessels a value in most places of about 4 I, from which the value 3 I is obtained for the ionisation in the free atmosphere, after subtraction of the secondary radiation at the walls. Since this value is much more certain than that obtained above by rough approximation of the uranium and thorium radiation, we will take, as the most probable mean value of the action of the γ-rays from the ground

$$q_2^{(\gamma)} = 3 \text{ I.}$$

The total β- and γ-radiation of the ground thus gives the ionisation :

$$q_2 = q_2{}^{(\beta)} + q_2{}^{(\gamma)} = 3\cdot1 \ \mathrm{I}.$$

Finally, we must take into account the ultra-gamma radiation (q_3) in the neighbourhood of the ground. Estimation of this factor is not easy, since we only know its effect in metal vessels, and do not know with certainty what fraction of the ionisation is due to secondary radiation from the metal walls. On the assumption that, as with the γ-rays of radioactive substances, three-quarters of the effect in closed vessels is pure volume ionisation, it is necessary to decrease by 25 per cent. the value obtained in metal vessels for the ultra-gamma radiation (1 to 2 I) in order to obtain the value in free air. In this connection it must not, however, be forgotten that any radiation reaching the earth's surface from above (water surfaces included) will excite secondary radiation,[1] and that the amount of ionisation primarily developed in the free air by the ultra-gamma radiation must be increased by this quantity. For the estimation of the order of magnitude of the action of the ultra-gamma radiation in proximity to the ground it will be assumed, as an approximation, that the secondary radiation effect at the earth's surface referred to is roughly equal to the secondary radiation effect at the wall of an ionisation vessel. We may, therefore, take as the mean value of the ionisation due to the ultra-gamma radiation the value

$$q_3 = 1\cdot5 \ \mathrm{I}.$$

As the combined effect of all the permanently active ionising agencies over dry land we therefore obtain as an average

$$q = q_1 + q_2 + q_3 = 4\cdot9 + 3\cdot1 + 1\cdot5 = 9\cdot5 \ \mathrm{I}.$$

The radioactive substances in the air (q_1) thus yield about

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[1] V. F. Hess, *Wien. Ber.*, **121**, 2031 (1912), ascribes the difference in ionisation as found over dry land and over water partly to this effect.

half the total ionisation. q_1 may vary between 0 (in the middle of the ocean) and 30 I; q_2 (earth radiation) between 0 (over water) and about 15 I. The third term (ultra-gamma radiation) is be much less variable.

We may now compare these figures with the actually observed amounts of ionisation. As the mean value of the number of small ions in the air we will take the value $n = 700$ per cubic centimetre. Since a much larger number of large ions and dust nuclei is often present over land, we must assume the linear recombination law of Schweidler,

$$q = \beta' . n,$$

instead of the ordinary square law.

The values of the " diminution constant " β' determined by Schweidler in pure country air vary between 16 and $19 . 10^{-3}$. Introduction of these numerical values gives as the total ionisation about

$$q = 10 \text{ to } 13 \text{ I.}$$

The sum of the effects of all ionisers calculated by us ($9 \cdot 5$ I) thus agrees as well with the ionisation calculated from the rate of disappearance of ions as can be expected in view of the great variability of the factors which enter and the shortage of experimental data.

2. Ionisation Balance over the Sea.—It has been well known for twenty years that the conductivity and the number of small ions are as great over the sea as over dry land. While no certain knowledge was available as to the emanation content of the air over the ocean, it was assumed that a considerable quantity of the emanation from dry land would be carried over the sea, where it would act as the most important ioniser. The fundamental investigations of the Carnegie Institution [1] under

[1] Carnegie Institute of Washington, Publication No. 175, Vol. III. (Researches), 1918. *Terr. Magn.*, **27**, 187 (1924).

L. A. Bauer, W. F. G. Swann, and J. Mauchly showed, however, that the emanation content in parts of the ocean far removed from land is about 100 times smaller than over dry land (*cf.* § 19 (3)). Since such parts amount to about half the earth's surface, it is evident that the explanation of the ionisation observed over the sea is one of the most important tasks of the investigators of atmospheric electricity.

As has been said, the radioactive substances in the air play hardly any part in the ionisation balance over the sea. The thorium products are entirely absent ; the radium products account for an ionisation of only about 0·03 I. Equally small is the action of the radioactive substances in the water. Simpson (*loc. cit.*) estimates the ionisation due to the γ-rays of the elements of the radium group in the sea at 0·01 I. The ionisation observed over the sea can, therefore, not be ascribed to the traces of radioactive decomposition products present in and above the sea.

The discovery of the ultra-gamma radiation in the year 1912 first opened the way for an explanation of the ionisation over the ocean, for this radiation is equally active over land and sea. We have estimated the ionisation due to this cause as 1·5 I. If we assumed the validity of the ordinary square recombination law over the sea, as would only be strictly true in air perfectly free from nuclei, the following ion number would be obtained from the ionisation and the recombination coefficient a $(1·6 . 10^{-6})$:

$$n = \sqrt{q/a} = 970.$$

This value is still somewhat higher than that actually observed, which amounts to about 500 to 600 per cubic centimetre. Now the air over the ocean must also contain Aitken nuclei, though the average number of nuclei present is certainly smaller than over land, and Schweid-

ler's diminution constant should, therefore, be smaller ; from the agreement as to order of magnitude of the observed ion number with that calculated by the square law, it may therefore be concluded that the ultra-gamma radiation alone is sufficient to produce the observed ionisation.   The differences between the ion numbers observed on different seas may very probably be ascribed to differences in the emanation content of the air (Bauer and Swann).   More accurate calculations cannot be made at the present time owing to the lack of direct determinations of the diminution constant over the sea.

If the ultra-gamma radiation had not been discovered, it would have been necessary to conclude from the observed ionisation over the sea that there existed an unknown ioniser whose action over dry land might easily be overlooked on account of the strongly preponderating influence of the radioactive substances present there.

3. The Ionisation in the Free Atmosphere up to the Limits of the Troposphere.—Observations in flying machines have shown that conductivity and ion number rise with increasing height above the ground, at first slightly, and then rapidly from about 3 km. upwards. Consideration of the ionisers which are active in these regions make it easy to understand this behaviour.   At first, during the first kilometre of height, the radiation from the radioactive substances in the earth diminishes. The amount of thorium products in the air diminishes rapidly, and the quantity of radium emanation also falls at least by about half its value for every 1,000 to 1,200 metres rise.   This disappearance of important sources of ionisation is, however, soon compensated by the increase of the ionisation produced by the ultra-gamma radiation. A. Wigand,[1] on the basis of Kolhörster's measurements of the ultra-gamma radiation in zinc vessels, has calculated the ionisation produced by this radiation in the free

[1] *Phys. Zeitschr.*, **25**, 445 (1924).

atmosphere, making plausible assumptions as to the effect of the secondary radiation at the walls and taking into account the decrease in the density of the air with height. The curve (Fig. 14) shows Wigand's results. In the lowest 3 km. the points on the curve correspond, not to the total ionisation, but only to the ionisation by
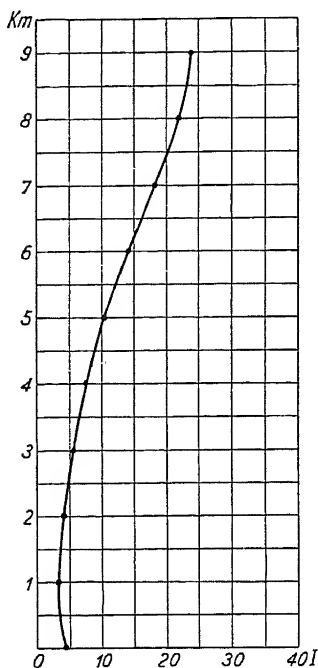
FIG. 14.—Increase of ionisation with height (Wigand).

γ-rays and ultra-γ-rays. The effect of the α- and β-radiation of the emanation and its decomposition products must, therefore, be added in this region. The radioactive substances are often almost entirely absent at heights above 3 km. (Wigand), and the curve therefore corresponds very well with the actual conditions from there upwards. Comparison with Kolhörster's curves for the ionisation in airtight closed vessels shows that in the free atmosphere the ionising power increases much more slowly with height. From 8 km. up the increase becomes still more slow, and at 9 km. the total ionisation is 23·4 I, as against 10·1 I at 5 km. The few available observations of ion number and conductivity made on balloon ascents and aeroplane flights show, as Wigand points out, a noticeable agreement with this curve.

As we have seen, our ionisation balance, i.e., the comparison of the effect of the ionisers with the observed ionisation, works out satisfactorily for the surface of the earth over dry land and sea, and also for the free atmo-

sphere as far as it is readily accessible to us. It must not be forgotten that this balance is based on average values taken from different places. It would be an important piece of work for future investigation to lay the foundations of a more accurate balance by simultaneous observation of all the electrical factors at one spot.

§ 28. The Electrical Conductivity and Ionisation of the Upper Layers of the Atmosphere.

1. Composition and Physical Properties of the Upper Layers of Air.—Before passing to a consideration of the state of ionisation of the upper atmosphere, it must be mentioned that even at the present time our knowledge of the general physical properties and constitution of the atmosphere in the stratosphere [1] are extremely scanty. Direct measurements of even the most important meteorological factors, such as atmospheric pressure and temperature, made by recording apparatus in pilot balloon ascents, are only available for heights up to about 35 km. All that can be said about the layers of the stratosphere above this is merely the result of indirect, and often extremely doubtful, conclusions. This is especially true of the electrical properties of the stratosphere ; there is not, for example, a single direct measurement of the conductivity, the potential gradient,[2] or other important electrical factors for heights above 10 km. As far as it is possible to draw reasonable conclusions as to the course of these quantities in the stratosphere from their behaviour with increasing height in the troposphere, it is to be expected that up to heights of, perhaps, 20 km. the electrical conductivity will still further increase, while the potential gradient sinks practically to zero. For

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[1] In mean latitudes the lower boundary of the stratosphere may be taken as 11 km.

[2] Quite recently (1926) P. Idrac obtained a few values of the potential gradient in a pilot balloon ascent to 20 km. At this height the gradient sinks to less than 2 volts per metre.

heights of 20 km. upwards, however, we are forced to depend upon indirect conclusions which may be drawn from other geophysical facts, as will be explained later.

It is quite within the bounds of possibility that direct measurements at heights of more than 40 km. might be obtained by the sending up of specially-constructed rockets fitted with recording apparatus. Rockets of this kind may very possibly be obtainable in the near future, and their applicability for collecting important data at the greatest heights has been seriously discussed from the meteorological standpoint.[1]

It is not possible to speak of a definite upper limit of the atmosphere. It must be assumed that even the space in which our planet moves contains traces of gaseous substances in a state of extreme dilution, and that the density of the atmosphere finally falls asymptotically at a height of many hundred kilometres to a value identical with that of interplanetary space.

Many meteorological phenomena of an optical nature, such as twilight, luminous night clouds, the aurora and shooting stars, point to the fact that at heights of 40 to 700 km. gases exist at a concentration which is still sufficient to produce certain optical, electrical and thermal phenomena.

Within the troposphere, on account of the continual action of air currents and mixing processes, the relative proportions of the gaseous constituents of the air do not alter with the height ; in the stratosphere, on the other hand, gradual separation into layers takes place, as must be expected from Dalton's Law, when the force of gravity is simultaneously active. Accordingly the lighter gases, such as helium and hydrogen, must outweigh the other constituents of the air more and more the higher the layer in question.

[1] W. J. Humphreys, *Bull. National Research Council, Washington, D.C.*, Vol. X., Part 3, No. 53, 1925, p. 52.

A. Wegener [1] has advanced the hypothesis that, in addition to the known gases contained in the air, there is yet another lighter gas, " geocoronium," present in the upper layers of the atmosphere, which here plays a similar part to the coronium in the sun's atmosphere. In his article on " The Thermodynamics of the Atmosphere " [2] Wegener writes as follows : " Although in the system of the elements as it is known to-day no place remains for such an element, yet the corona of the sun shows that there is a material substance of some kind present there which behaves as a lighter gas of this nature ; it must be assumed that this consists of atomic residues (' electron gas ')."

The composition of the air, expressed in volume percentages at various heights, would, according to Wegener's calculations, be as follows (round figures are used in the table from the second row onwards) :

Height km.	Geocoronium per cent.	Hydrogen per cent.	Helium per cent.	Nitrogen per cent.	Oxygen per cent.	Argon per cent.
0 (ground)	0·00058	0·0033	0·0005	78·1	20·9	0·94
20	0	0	0	85	15	0
40	0	1	0	88	10	0
60	4	12	1	77	6	0
80	19	55	4	21	1	0
100	29	67	4	1	0	0
120	32	65	3	0	0	0
140	36	62	2	0	0	0

If the hypothesis of the still lighter gas geocoronium is not accepted, the hydrogen content (volume per cent.) would be obtained by addition of the second and third vertical columns, e.g., for 100 km. the hydrogen content will be 96 per cent.

The diminution of pressure with height may be seen

[1] *Phys. Zeitschr.*, **12**, 170, 214 (1911).
[2] " Handbuch der Physik," Vol. XI., p. 160 (Berlin : J. Springer 1926).

from the following table, calculated by Humphreys [1] on the assumption that the stratosphere is at constant temperature (— 55°), and that hydrogen is the lightest gas in the atmosphere :

Height km.	Pressure mm.	Height km.	Pressure mm.	Height km.	Pressure mm.
15	89·66	50	0·40	90	0·0081
20	40·99	60	0·094	100	0·0067
30	8·63	70	0·027	110	0·0059
40	1·84	80	0·0123	120	0·0052

At heights of 30 km. upwards there are thus pressures of the same order of magnitude as the pressures at which the phenomena of luminous discharge in Geissler tubes are observed. This is of importance in the explanation of the electrical nature of the aurora borealis.

As regards the vertical temperature distribution, it will suffice to say here that the fairly regular decrease of temperature in the troposphere—on the average about 4° to 7° per kilometre of height—comes to an end in the lowest layers of the stratosphere. From there upwards there occurs again a small increase of temperature (upper inversion), and the mean temperature of the stratosphere up to 30 km. may be set at about — 55° C. The temperatures at still greater heights are unknown.

The conclusion that the highest layers of the atmosphere, at 70 to 80 km., consist chiefly of hydrogen is further supported by the fact that the samples taken at heights of only 8 to 9 km. contain appreciably more hydrogen than samples taken near the earth.

It is necessary to remark here that several authors

[1] Hann-Süring, " Lehrb. d. Meteorologie " (4th ed., Leipzig, 1922), p. 9.

assume that layers exist in the stratosphere which are fairly rich in ozone, especially by day, when the ultra-violet region of the solar spectrum exerts an ozone-forming and ionising action.   It has also been concluded that this ozone-rich layer actually exhibits a selective absorption for ultra-violet light of short wavelength, and that this is the reason why in the troposphere, even at 10 km. height, the solar spectrum does not extend beyond a wavelength of 2,890 Å. in the ultra-violet.

In any case, the fact must be borne in mind that the ultra-violet region beyond $\lambda = 1,350$ Å, which exerts a strong ionising influence in air, is only present in the middle and upper layers of the stratosphere.

The ordinary liquid or solid substances present in the air, such as water or ice particles, and dust, hardly play any part in the stratosphere.   Very finely divided ash and volcanic dust may penetrate to great heights in these layers during volcanic eruptions, and remain suspended for months, as is shown from the increase of opacity of the air after such eruptions.

There also remains the possibility that cosmic dust or finely-divided matter from the sun, driven by the light pressure (Sv. Arrhenius, J. A. Fleming), may reach the upper layers of the atmosphere.   The photoelectric action of the longer wavelengths in the ultra-violet of the solar spectrum may also cause this " solar dust " to give off electrons, thus forming positive and (by agglomeration of electrons) negative ions.

2. **Hypotheses of the Ionisation of the Upper Air.**— There are essentially three groups of phenomena whose explanation requires the hypothesis that the upper layers of the stratosphere must possess a relatively high electrical conductivity : (1) the daily variations of the terrestrial magnetism ; (2) the luminous electrical phenomena in the uppermost layers of air, known as aurora borealis ;

(3) the results of experience as to the transmission of electric waves to very great distances.

As the causes of the great electrical conductivity of the upper layers, the following ionisers must chiefly be borne in mind :

(a) Ultra-violet radiation from the sun.

(b) Corpuscular radiation from the sun.

(c) The *höhenstrahlung* (ultra-gamma rays).

The source of ionisation given under (a) can only be acting as an ioniser during the day. A. Schuster [1] explains the daily variations of terrestrial magnetism by induction currents in the stratosphere ; to enable these to occur in the upper layers of the stratosphere a conductivity of about 9.10^7 electrostatic units (cm.$^{-1}$) would be necessary. W. F. G. Swann,[2] in a criticism of Schuster's theory, has estimated the electrical conductivity produced by ultra-violet radiation at 100 km. to be $\Lambda = 8.10^4$ electrostatic units, or about 10^{-16} electromagnetic units. This value is about 4.10^8 times greater than the mean conductivity of the air at the earth's surface. Elias obtained values about 1,000 times greater.

According to Fleming, this ionising effect would only extend from above down to a height of about 50 or 60 km., since the active wavelengths ($< 1,350$ Å.) of the solar spectrum are wanting in the lower layers.

After sunset the ions so formed will disappear by recombination. Accordingly, this ionisation is not to be regarded as permanent, and is only applicable to the explanation of certain peculiarities in the transmission of electric waves.

Very recently F. A. Lindemann [3] has referred to a hypothesis of R. d'E. Atkinson which attempts to explain

[1] *Phil. Trans.*, **208**, 163 (1908).

[2] *Terr. Magn.*, **21**, 1–8 (1916).

[3] *Proc. Roy. Soc.*, A, **111**, 1–13 (1926).

the ionisation of the upper air by night also ; according to this view, the ozone formed during the day by the ultra-violet rays from the sun is slowly converted into oxygen during the night, under formation of ions. At present this hypothesis is without any experimental support.

The second source of ionisation is the corpuscular radiation of the sun, mentioned under (b). This may consist either of rapidly-moving electrons ("helio-kathode rays "), a-rays, or other positively-charged atoms (e.g., hydrogen particles) of high velocity.

The hypothesis of electron emission by the sun was first advanced during investigation of the aurora borealis, and it is so well supported on many sides that the penetration of such solar cathode rays into the lower layers of the stratosphere may be regarded as almost certain. The experimental foundation of this cathode-ray theory of the aurora is due to Kr. Birkeland ; [1] the theory itself was chiefly worked out by K. Störmer.[2]

The suggestion put forward by J. Vegard,[3] that the aurora is caused by a-particles from the sun, has found little support, and has been abandoned by that author himself. It is, however, probable that, in addition to electrons, positive corpuscular rays (e.g., hydrogen particles) are also emitted.[4]

At present there is no starting point for an estimation of the distribution and ionising effect of the solar corpuscular rays. S. Chapman calculates that a-rays from the sun with an initial velocity of 20,000 km./sec. may penetrate into the atmosphere to the 80 km. level. According to P. J. Elias, a very sharp rise in the ionisation should be

[1] " Expéd. Norveg., 1899–1900 " (Christiania : J. Dybwad, 1901) ; Arch. scien. phys. et natur. (4), 1, 497 (1896).

[2] Vidensk. Skrifter, No. 3, Christiania, 1904 ; Compt. Rend., 142, 1580 ; 143, 140, 408, 460 (1906).

[3] Phys. Zeitschr., 12, 185 (1911) ; 14, 677 (1913).

[4] E. v. Schweidler, Terr. Magn., 27, 105 (1922), and 28, 50 (1923) ; R. Swinne, Phys. Zeitschr., 17, 529 (1916) ; J. Stark, Ann. d. Phys. (4), 54, 598 (1917).

expected between the heights of 80 and 85 km. on account of such rays.   Owing to the deflection caused by the earth's magnetic field, it is to be anticipated that charged corpuscular rays will be concentrated into definite annular zones in the neighbourhood of the earth's magnetic pole (auroral zone).

The third ioniser active in the stratosphere is the *höhenstrahlung* (ultra-gamma radiation).   The ionising action of this is fairly well known in the lowest layers up to 9 km. (*cf.* § 23 (6)).

The conductivity of the air (*cf.* § 4) depends upon the number of ions present and their mobility.   The ion number itself is determined by the ionisation and the recombination (§ 3, § 26).

Now, since the dependence of the mobility and the recombination on pressure is fairly well known, all that is necessary for calculation of the conductivity of the air at great heights is a knowledge of the ionisation due to the above-mentioned three chief sources of ionisation. As regards the ultra-violet and corpuscular radiations from the sun, no quantitative data are available.   H. Benndorf [1] has, however, succeeded in calculating a value for the conductivity produced in the troposphere and stratosphere by the ultra-gamma radiation in remarkable agreement with the measurements which have been obtained up to 9 km.   According to Benndorf, the conductivity of the air due to the ultra-gamma radiation alone increases according to an exponential law.   The following table and curve give the values thus calculated for the conductivity Λ of the atmosphere in electrostatic units (cm.$^{-1}$), and also the ratio of Λ to the conductivity Λ_o at the earth's surface for the two extreme values $\mu/\rho = 2\cdot26 \,.\, 10^{-3}$ cm.^{2}/gm. and $\mu/\rho = 4\cdot52 \,.\, 10^{-3}$ cm.^{2}/ gm. of the mass absorption coefficient (see p. 141) of the ultra-gamma radiation.   Since the latter value is taken

[1] *Phys. Zeitschr.*, **27**, p. 626 (1926).

directly from balloon experiments up to 9 km. (Kolhörster), it most probably represents best the state of affairs in the free atmosphere. Λ_o is taken as $3 \cdot 10^{-4}$ E.S.U.

It may be seen from the two curves that at 80 km. there is a very sharp increase in the conductivity. Even at that height the conductivity is already 10^9 times greater than at the earth's surface. The conductivity at 80 km. is from 3 to $9 \cdot 10^5$ cm.$^{-1}$, *i.e.*, about as great as that of dry earth. Since the *höhenstrahlung* acts equally strongly by day and night, the fact that the high conductivity at 60 km. and over persists at night also is finally explained.

It is noteworthy that the ultra-gamma radiation at these heights is sufficient of itself to account for the existence of that conducting layer (Heaviside layer) whose existence is proved by experience in the propagation of electric waves, and also quite recently by direct experiment with such waves (see below). The other possible sources of ionisation mentioned above are either unequally distributed from the geographical point of view (solar corpuscular rays) or variable with time, like the ultraviolet light of the sun, which is only active during the daytime.

It cannot be doubted that both

Height in kilometres	0	9	12	20	40	60	80	100	120
For $\mu/\rho = 2{\cdot}26 \cdot 10^{-3}$ $\{\Lambda$	$3 \cdot 10^{-4}$	$2{\cdot}9 \cdot 10^{-3}$	$5{\cdot}3 \cdot 10^{-3}$	$3{\cdot}5 \cdot 10^{-2}$	$8{\cdot}8$	$3{\cdot}5 \cdot 10^{3}$	$2{\cdot}9 \cdot 10^{5}$	$1{\cdot}8 \cdot 10^{6}$	$3{\cdot}0 \cdot 10^{6}$
$\{\Lambda/\Lambda_o$	1	$9{\cdot}6$	18	116	$29{,}000$	$1{\cdot}2 \cdot 10^{7}$	$9{\cdot}0 \cdot 10^{8}$	$6{\cdot}0 \cdot 10^{9}$	$1{\cdot}0 \cdot 10^{10}$
For $\mu/\rho = 4{\cdot}52 \cdot 10^{-3}$ $\{\Lambda$	$3 \cdot 10^{-4}$	$6{\cdot}0 \cdot 10^{-3}$	$1{\cdot}4 \cdot 10^{-2}$	$1{\cdot}1 \cdot 10^{-1}$	$2{\cdot}8 \cdot 10^{3}$	$1{\cdot}2 \cdot 10^{4}$	$9{\cdot}4 \cdot 10^{5}$	$5{\cdot}8 \cdot 10^{6}$	$9{\cdot}8 \cdot 10^{6}$
$\{\Lambda/\Lambda_o$	1	22	46	350	$94{,}000$	$3{\cdot}7 \cdot 10^{7}$	$3{\cdot}1 \cdot 10^{9}$	$1{\cdot}9 \cdot 10^{10}$	$3{\cdot}3 \cdot 10^{10}$

the corpuscular radiation and the ultra-violet light from the sun cause considerably more ionisation at a height of 70 km. and over than the *höhenstrahlung*.

From the electrical point of view the stratosphere must be regarded as divided into two parts : the layers from 10 up to 60 km. are only moderately ionised, since in those regions no permanently active ionisers are present besides the *höhenstrahlung* (lower stratosphere); above 60
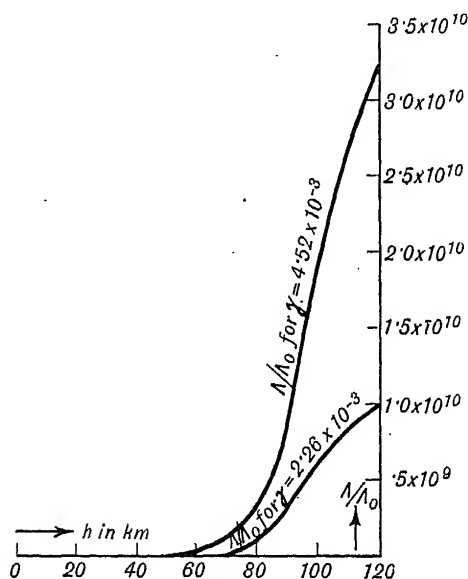
FIG. 15.

to 70 km., on the other hand, there are layers, consisting mainly of hydrogen, which are strongly ionised, and in which free electrons are certainly always present in large numbers (upper stratosphere). The upper stratosphere is also called the Heaviside layer (also Kennelly-Heaviside layer, *cf.* § 8, p. 38, footnote). The ionisation produced by ultra-violet light will, of course, cause the limit of the strongly-ionised layer to move 20 to 30 km. lower by day.

If it is assumed that the carriers of electricity in the

uppermost layers are chiefly hydrogen ions, then, according to R. Mesny,[1] about 10^7 such ions per cubic centimetre must be present at a height of 100 km. G. V. Watson,[2] Fleming and others have made similar estimates.

According to the latest theories of the propagation of electric waves, the important thing is not so much the conductivity of the Heaviside layer as the fact that besides the hydrogen atoms there are also a sufficient number of free electrons present. A. H. Taylor and E. C. Hulburt [3] calculate the number of free electrons at a height of 250 km. as 100,000 per cubic centimetre.

3. The Transmission of Electric Waves over the Earth's Surface, and the Influence of the Ionisation of the Upper Layers of the Atmosphere.—The chief problem of wireless telegraphy and telephony may essentially be summarised as follows : A sphere of moderate electrical conductivity (earth) is isolated in space ; on its surface there is a transmitting station of given dimensions, which emits electrical waves equally in all directions. According to what law does the energy falling on a receiver (signal strength) diminish with the distance, and what are the conditions influencing the range ?

Many authors have dealt with this problem ever since the time when Marconi first succeeded in bridging great distances. It was established experimentally that, for long wavelengths at least, the intensity of the signal was approximately inversely proportional to the distance d of the transmitter and to the wavelength λ, being further dependent on an absorption term, as shown by the empirical formula of L. W. Austin :

$$S = 120\,\pi \cdot \frac{h\mathrm{I}}{\lambda d} \cdot e^{-0.0015\frac{d}{\sqrt{\lambda}}}.$$

[1] R. Mesny in E. Mathias's " Traité d'Electricité Atmospherique, p. 406 (Paris, 1924).

[2] *Proc. Roy. Soc.*, A, **95**, 83 (1918).

[3] *Phys. Rev.* (2), **27**, 189 (1926).

Here h is the height of the transmitting aerial, and I the current strength in the aerial; λ and d are expressed in kilometres.

The first formulæ obtained theoretically [1] showed no agreement with practice. The ranges and signal strengths actually obtained at great distances were far greater than had been calculated. It was then concluded that the transmission of electric waves must be regarded as a conduction process, and that some kind of conduction of the waves took place in the well-conducting surface layer of the earth similar to the propagation of the electrical waves on Lecher wires (theory of surface waves).

As the range of transmission of wireless signals was continually increased in practice, until at length clear reception was obtained at distance of 10,000 km. (one-quarter of the earth's circumference), it was found that great differences were observable in the signal strength by day and by night, as well as anomalies at sunrise and sunset. Accordingly, the idea gradually gained ground that the strongly ionised layer at a height of 80 km. and more, or its lower limiting surface, caused a reflection of the electric waves, and so enabled them to be received at places very far distant. The existence of this layer was, as has already been mentioned in § 8, suggested almost simultaneously in the year 1902 by Kennelly and Oliver Heaviside, independently from one another; before them Balfour Stewart (1883) had advanced a similar idea.

The electrical waves emitted by a transmitting station on the earth's surface are, according to this theory, propagated in a medium which is a fairly good insulator (troposphere and lower stratosphere) between two well-conducting, concentric spherical surfaces (the earth's surface and the lower limit of the Heaviside layer). It is thus understandable that almost the whole of the

[1] For a summary of the literature, see H. Schindelhauer, *Meteorol. Zeitschr.*, **37**, 177 (1920).

energy emitted by the antenna in the form of waves remains within this badly-conducting space.

It has since been found that this conception, although subject to subsequent modification, must be essentially right.

Originally it was assumed that the Heaviside layer must have a fairly sharply-defined limiting surface, since otherwise it was impossible to explain the occurrence of a reflection of the waves. Fleming attempted to explain how such a relatively sharp boundary could come into existence.

A new conception was introduced by W. H. Eccles.[1] This author showed that, besides the reflection, a deviation or refraction of the waves must also occur in the regions of the stratosphere, less strongly ionised by the ultra-violet rays, lying below the Heaviside layer (ionic refraction). The electric waves penetrate this layer from below and suffer a gradual change in direction in such a way that they run parallel to the earth, or, finally, even sharply downwards. This ionic refraction is explained by the fact that the velocity of propagation is greater in the ionised layer. Plane wave fronts are, therefore, bent forwards in their upper portions so that the waves can finally reach the earth again. This theory of ionic refraction of Eccles was able to explain many of the anomalies known at that time (1912) in the reception of electric waves at stations far removed from the transmitter. The increased range by night, for instance, was due to the fact that, owing to the disappearance of the ionisation of the lower stratosphere produced by the ultra-violet rays, the waves coming from the transmitter at a large inclination to the horizontal were not reflected until they reached the much higher Heaviside layer; while by day the ionic refraction of the waves occurred much lower, and so brought the

[1] *Proc. Roy. Soc.*, A, **87**, 79 (1912).

waves to earth again at a shorter distance from the transmitter.

The fact that strong ionisation diminishes the transparency of the air to electric waves was made clear by Fleming,[1] by an optical analogy, in a manner easily understood by the layman : if there are numerous air bubbles in water, all the light is totally reflected by them and the water appears opaque. R. Mesny (*loc. cit.*, p. 185) calculates that, on Eccles' theory, the velocity of propagation of the electric waves at a height of 30 km. is already about 0·5 per cent. greater than at the surface of the earth. This difference would suffice to explain quantitatively the bending of the path of the waves towards the earth.

G. V. Watson [2] has also developed a theory of the propagation of electric waves between two concentric conducting spherical surfaces, with which he obtained a transmission law for long waves in good agreement with Austin's formula, and thus in fairly good agreement with practice. He places the Heaviside layer at a height of 100 km.

All these theories of wave propagation, together with the older ones not mentioned, fail in the case of short waves, and it is evident that there are important factors still remaining unknown.

As a matter of fact, the influence of the earth's magnetic field—which is present everywhere and at all times—on the propagation of electric waves has not been considered until quite recently, from 1924 onwards. The fundamental theory of Sir Joseph Larmor [3] must be mentioned in this connection. Larmor considers the motion of charged particles (ions or free electrons) in the Heaviside layer under the simultaneous influence of the constant magnetic field of the earth and the alternating

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[1] *Nature*, **109**, 140, 177 (1922).

[2] *Proc. Roy. Soc.*, A, **95**, 83 (1918).

[3] *Phil. Mag.* (6), **48**, 1025 (1924).

electric field of the incoming waves. This alternating electromagnetic field naturally causes the ions and electrons to vibrate with it, and this will only be possible with great loss of energy, *i.e.*, with simultaneous absorption of the waves, if the vibration of the particles encounters any appreciable frictional resistance in the air. Thus, if a train of electric waves can pass through an ionised gas without appreciable absorption, the frictional influence must be vanishingly small. Larmor shows that this is only the case, first, when the energy-consuming collisions of the vibrating electrons or ions with gas molecules are infrequent (*i.e.*, when the mean free path of the ions and electrons is large in comparison with the amplitude of the vibration in the alternating field); and, secondly, when the frequency of the vibration is great in comparison with the average number of collisions per second of the ions and electrons with gas molecules. Both conditions occur in the region of the Heaviside layer for hydrogen ions, and to a less degree for electrons.

The energy loss, which may then be calculated for waves of average wavelength by plausible assumptions as to the number of ions or electrons present, is very small, and it is therefore readily understandable that such waves may travel many hundreds of kilometres in the ionised layer without serious weakening.

Larmor also calculates how much the number (N) of electrons per cubic centimetre must increase with the height (h) in order to produce within the Heaviside layer a bending of the wave path parallel to the earth's surface. He obtains the value $dN/dh = 3 \cdot 10^{-6}$; this means that, on the assumption that the rays keep within an electron-rich layer of only 1 km. vertical thickness, the upper side of this " effective layer " must contain only 0·3 electrons per cubic centimetre more than the under side. Greater differences of concentration

would cause the wave path to be deflected towards the earth.

This bending of the rays is, according to Larmor's theory, greatly dependent upon the wavelength; for waves of 60 metres length and less it will be vanishingly small.

This is contradicted by recent experiments of Reinartz [1] and Taylor,[2] which show that the short waves are apparently more strongly refracted than might be expected.

Even before this the difficulties experienced in obtaining great ranges in broadcasting with moderate wavelengths (200 to 600 metres), and the lack of constancy in the strength of the received signals, showed that some kind of selective effect, some disturbing influence peculiar to the middle range of wavelengths, must exist.

Further development of the theory of the propagation of electric waves had to take account of this. The first extension of the theory is due to E. V. Appleton.[3] Complete theories of this kind have been worked out independently by H. W. Nichols and J. C. Schelleng,[4] also by A. Hoyt Taylor and E. O. Hulburt.[5] They may be regarded as a modification and development of Larmor's theory, but the applicability of the latter in the region of longer wavelengths remains unaltered.

The selective effect referred to may be seen by consideration of the motion which an electron (charge e, mass m) is forced to execute under the influence of the alternating electromagnetic field of the oncoming waves and the simultaneous action of the earth's magnetic field (field

[1] "Q. S. T.," 9, 9 (April, 1925).

[2] Proc. Inst. Radio Engineers, 13, 677 (December, 1924).

[3] Proc. Phys. Soc. London, 37, 2nd part, 22D (February, 1925).

[4] The Bell System Tech. Journ., 4, 215–234 (1925); Science (N.S.), 61, 288 (1925), No. 1576.

[5] Phys. Rev. (2), 27, 189 (1926); Science (N.S.), 62, 183 (1925) No. 1599.

strength H). The amplitude of the component of vibration perpendicular to the magnetic field H has its maximum value when the frequency of the electric wave fulfils the equation

$$\nu_0 = \frac{1}{2\pi} \cdot \frac{e}{m} \cdot H,$$

i.e., when the wavelength is

$$\lambda_0 = 2\pi \cdot \frac{m}{e} \cdot \frac{c}{H}.$$

Replacing $\frac{e}{m}$ (the specific charge of the electron) and c (the velocity of light) by the known numerical values, and taking the field strength of the earth's magnetic field as $H = 0.5$ Gauss, this critical wavelength is

$$\lambda_0 = 214 \text{ metres.}$$

For this critical wavelength or frequency, which varies, however, with the value of the earth's field strength, the vibration of electrons produced by the passage of the waves will be particularly violent; the wave propagation will, therefore, be most strongly influenced by the induced vibration of the electrons in the Heaviside layer for waves of the critical wavelength λ_0; a particularly strong absorption of these waves will result. It must be emphasised that the corresponding value of λ_0 for vibrating particles of atomic dimensions (*e.g.*, hydrogen ions) is 1,800 times larger, and therefore outside the range of wavelengths used in practice.

As regards the propagation of the waves, different cases arise according to the particular direction of transmission. If linearly-polarised electric waves are assumed, with, say, the vibration of the electrical vector in the vertical plane, then, according to Nichols and Schelleng, transmission in the direction of the earth's magnetic field (chief component north and south) will result in a separation of the waves into two opposite circularly-polarised waves of

different velocity, so that an actual separation in space into two wave trains may result. For short waves this does not occur, but there is merely a rotation of the plane of polarisation of the electric wave. In transmission from east to west, or *vice versâ*, double refraction occurs ; that is, the waves become separated into two wave rays polarised in directions at right angles to each other. The case may even arise where one ray is bent towards the earth in the Heaviside layer, while the other is bent upwards.

It is worthy of note that certain anomalies of wave propagation which have only been discovered quite recently may be explained by the new theory. Here only one of these phenomena can be discussed further.

It has been established that for short waves ($\lambda < 50$ m.) the strength of reception for a constant transmitting power (*e.g.*, 5 kilowatts) diminishes fairly rapidly with the distance from the transmitter, and falls practically to zero at 100 to 150 km. At greater distances from the transmitter the signals remain inaudible ; but at a still greater distance they can again be detected, and a maximum of signal strength is again reached which falls only slowly with further increase of distance. The distance of the outer boundary of this " zone of silence " may be called the " skip-distance." This skip-distance depends, according to Taylor (*loc. cit.*) to a very great extent on the wavelength used ; its value by day for wavelengths of 16, 21, 32 and 40 metres, for example, is 2,100, 1,100, 640 and 280 km. respectively. The enormous ranges obtained with very short waves are thus explained.

The phenomenon of the zone of silence is a direct experimental proof of the reflection or refraction of waves in the Heaviside layer. By night the skip-distances, according to experiments of W. G. Baker and C. W. Rice,[1] are four or five times as great, since the reflecting layer then lies higher.

[1] *Science* (N.S.), **63,** No. 1626.(February, 1926).

Taylor and Hulburt (*loc. cit.*) have quantitatively explained these and other phenomena of the reception of short waves by means of the theory referred to. It appears that only the electrons, and not the ions in the upper layers, are of importance for the reflection and refraction of the waves. The reception of short waves (20 to 50 metres) at distances of 10,000 to 20,000 km. appears to be possible on account of the fact that they undergo a refraction in the upper layers of the atmosphere, and a reflection at the earth's surface, and that this process is repeated a number of times. Waves of smaller wavelength than 14 metres are not suitable for the attainment of great ranges. Waves of 60 to 200 metres can be reflected from the Heaviside layer with any angle of incidence.

According to these experiments, the number of electrons per cubic centimetre seems to reach its maximum value by day (10^5 per cubic centimetre) at heights of 110 to 250 km. The theory also appears to be capable of explaining certain distortions of the wave form, and variations of the received intensity (" fading ") (*cf.* (5) below).

4. Experiments for Determining the Height of the Heaviside Layer.—The height of the " reflecting " layer above the surface of the earth may not only be indirectly estimated, as shown in the previous section, but may also be determined by direct experiment. Up to the present two methods have been employed in practice.

The first, due to E. V. Appleton and M. A. F. Barnett,[1] may be briefly described as an " interference method." It depends on causing interference between the wave which passes from the transmitter directly over the earth's surface and that which is reflected from the Heaviside layer. The transmitting station (Bournemouth,

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[1] *Nature*, **115**, 333 (1925); *Electrician*, **94**, 398 (1925); *Proc. Roy. Soc.*, A, 109, 621 (1925).

England) was fitted with a device which caused the wavelength to vary continually over a known range in a definite interval of time '(10 to 30 seconds), the transmitting energy remaining constant. The receiving station, 140 km. away, had a constant sensitivity over the whole of the wavelength range employed. The wave which passed into the Heaviside layer, and then to earth (to the receiver), had accordingly a slowly-changing phase difference with the direct wave ; consequently, increases and decreases of strength, due to interference, were observable at the receiver. The experiments gave very distinct maxima and minima. The height of the reflecting layer was in this way estimated at 85 km. (by day). Naturally, this must be regarded as the average height of the active layer of electrons. The lower limit of the Heaviside layer will always, even by night, remain fairly indefinite. This means that for short wavelengths the boundary must (in comparison with the wavelength) be regarded as fairly diffuse ; for these wavelengths, therefore, refraction (bending of the rays) occurs. For long waves, on the other hand, the transition is sufficiently sharp to permit of reflection.

A second method for the practical determination of the height of the Heaviside layer was worked out by M. A. Tuve and G. Breit.[1] The sending and receiving stations (at distance l) form an equilateral triangle with the region of reflection in the Heaviside layer, lying at the height h km., which has to be determined. Wave trains ($\lambda =$ 71 metres) interrupted at regular intervals are now emitted by the transmitter, and registered by an oscillograph at the receiving station. The waves which have travelled by the indirect path over the two sides of the

[1] *Terr. Magn.*, **30**, 15 (1925) ; *Annual Report of the Director, Dept. of Terr. Magn., Carnegie Inst., Washington, D.C.*, No. 24, p. 176 (1925) ; *Nature*, **116**, 357 (1925).

triangle to the receiver are retarded, as compared with the direct wave, by a time

$$\tau = \frac{2h}{c} \left[\sqrt{1 + \left(\frac{l}{2h}\right)^2} - \frac{l}{2h} \right],$$

and they are therefore registered by the oscillograph in the spaces between the records of the direct waves. The time τ is determined from the record strips (in the actual experiments it was about $\frac{1}{3000}$ second), and then, by putting the known distance l between the two stations and the velocity of light c into the formula, the height h is determined. Tuve and Breit found values for h between 80 and 160 km. The height of the "reflecting layer" varies, as is known, with the time of day.

The last doubt as to the existence of the Heaviside layer must have been removed by these experiments, and the remaining opponents of this layer hypothesis [1] have a difficult position to maintain in the light of all these recent researches.

With considerable foresight, J. A. Fleming [2] even in 1915 realised that wireless telegraphy, and particularly the use of directional transmitters, would form an exceptionally helpful means of investigating the highest layers of the atmosphere. He says : " It is possible that, by using directive antennæ to send electric waves upwards at various angles and discovering where they chiefly come to earth again, we may be able to employ radiotelegraphy as an atmosphere-exploring agency, just as we can employ a searchlight to discover reflecting objects in clouds in the lower levels of the atmosphere."

The progress made since 1915 offers grounds for hoping that we shall eventually be able not only to measure the height of the Heaviside layer, but also to examine

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[1] *Cf.*, for example, R. A. Meissner, *Jahrb. f. drahtl. Telegr.*, **24**, 85 1924).

[2] *Electrician*, **75**, 348 (1915).

the lower-lying "ion clouds" or "ion banks" in the atmosphere, and their changes, by direct experiment.

5. Atmospheric Interference in Wireless Telegraphy and Telephony, and its Relation to the Phenomena of Atmospheric Electricity and Meteorology.—Although atmospheric interference in the wireless sense is to a large extent not connected with the processes of the upper atmosphere, we shall give a short summary of this question here, as the "atmospherics" are of general interest.[1]

The "atmospherics" are usually divided into four groups :

(1) Those which produce scratching noises in the telephones ("grinders").

(2) Those which cause sharp tapping and clicking noises.

(3) Those which cause hissing sounds.

(4) Those which cause sudden uncontrollable variations of the strength of reception ("fading effect").

As already mentioned, the "fading effect" is ascribed to interference phenomena between the oncoming waves, and only (1), (2) and (3) can be considered as purely atmospheric effects.

As to their cause little is known with certainty even now, in spite of the large amount of observations.

Some only of the atmospherics are of an oscillatory nature, with vibration periods of fractions of a second up to several seconds. Many are quite aperiodic, and on this account attempts to diminish interference from this cause by very sharply-tuned receiving circuits have only been partially successful.

"Atmospherics" are strongest in the summer months, and are stronger by night than by day. They are specially strong in tropical latitudes, where in unfavourable circumstances it is often necessary to use transmitting energies

[1] A general theoretical treatment of atmospheric interference in connection with wireless is given in "Die Hochfrequenztechnik," Vol. 1: Koerts, "Atmosphärische Störungen in der drahtlosen Nachrichtenvermittlung" (Berlin: M. Krayn, 1924).

for news distribution six or eight times greater than under favourable conditions of reception. The interfering noises were particularly troublesome when spark transmitters were still used. Later, working with musical notes (tuned spark or the modern heterodyne method), the telegraphic signs could more easily be picked out from the interfering noises.

Many investigators, such as C. de Groot and J. A. Fleming, are of the opinion that the most frequently occurring atmospherics of class (1) (grinders) are due to electrical processes in the upper stratosphere, or in the auroral zone. Others think that they are caused by electrons which reach the upper layers of the atmosphere from the sun. Fleming believes that recombination processes between the positively and negatively-charged particles in these high layers may be the cause of this type of atmospherics. At night, when the ionisation due to ultra-violet light decreases, they can then be more easily heard at the earth's surface. Silent discharges in the upper stratosphere must also be borne in mind as another possible cause.

Other classes of atmospherics in wireless telegraphy depend upon processes occurring in the troposphere. In particular, investigations with directional receivers by Watson Watt and others have shown that three-quarters of the atmospherics come from wide rain zones. Of course, thunder regions must also be sources of atmospherics, which may often make themselves felt at great distances. C. T. R. Wilson has shown that lightning discharges may also take place from thunder clouds upwards into the conducting layer, and such discharges will naturally be heard as atmospherics.

Experiments of R. Bureau in France show that atmospherics are very closely connected with the general weather distribution, or so-called "polar front." The connection is so close that it even suggests the converse

application of the study of atmospherics for weather forecasting and the prediction of thunderstorms. Another class of atmospheric seems to arise from definite centres, particularly from extended mountain ranges. The observation of the American polar explorer, Dr. Donald McMillan,[1] is remarkable ; in 1924, when he passed the auroral zone during a vigorous auroral display, he could notice no interference in the radio communication with America. This must not, however, be regarded as an indication that the electrical processes of the aurora borealis have no influence on electric waves. On the other hand, such interference would be more definitely felt in places far away, which received only waves which had been reflected in the region of the auroral zone ; alterations in the Heaviside layer in the zenith of the receiving station are apparently of small importance for the reception.

[1] *New York Times*, January 31st, 1925, p. 15.

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